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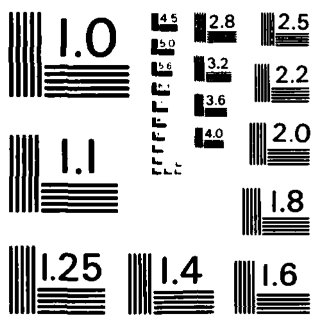

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Task II

HINGED HYDROSTATIC TRANSDUCERS

by

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1.0 Introduction

The initial proposal for this work was to prepare trial conformal hydrophones based on hinged arrays of individual transducer elements of three basic types. Choice of elements was based on previous work with composite transducers and consideration of sensitivity and durability. Polyurethane was chosen as a hinging material because it was an elastomer that had been used in other composite applications. Later this material was replaced by a flexable epoxy material that showed improved polymer/ceramic bonding, excellent self-bonding, and increased pot life. Many variations of element design were tested in 1"x1" arrays. Variations in elastomer hardness were tested. Different fillers were incorporated in the hinging material to make it hydrostatically compressable. Along with this work two flexable electrode systems were developed, for use with polyurethane and epoxy based polymers.

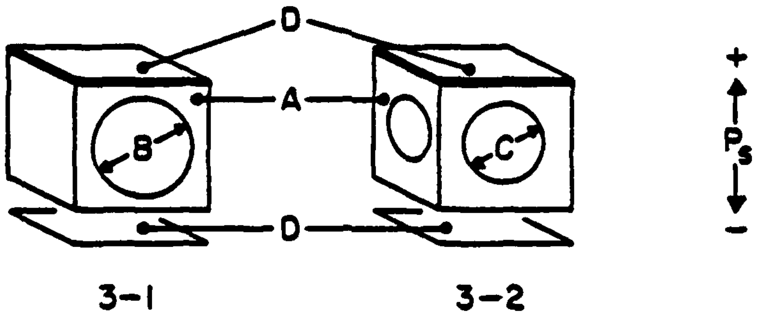
2.0 Fabrication of Individual Transducer Elements

Although the preparation of individual transducer elements has been described elsewhere (see initial proposal for references) and the design of these elements was not changed in any critical way, they have never been prepared in such large numbers at MRL. Furthermore, the details of the preparation, although done entirely through manual effort, should be useful in scale-up production of these devices.

2.1 Fabrication of 3-1 and 3-2 Perforated Block Elements by Extrusion

The design of the 3-1 and 3-2 elements is shown in Figure 2.1. Extrusion was chosen as the fabrication method for these elements since it was considered the most likely industrial technique for their production in mass quantities. A PVA/PZT pug was prepared and extruded through a square orifice with a fixed central pin to form the 3-1 perforation. After drying, green rods could be drilled to form the 3-2 perforation. After firing the rods were diced into individual cubes, electroded and poled.

This method was eventually abandoned because material with adequate shape tolerance and sufficiently low porosity could not be prepared on the primitive equipment available at MRL. However, this should not be a reason for overlooking this method as a viable production technique where proper equipment would be available. If high shear mixers, vacuum de-airing, and Auger type temperature controlled extruders were available, greater success could be achieved and the elements prepared with less effort.



A. PZT Block (4 x 4 x 4 mm)

B. Perforation: 109 mil diam., open or epoxy filled

C. Perforation: 96 mil diam., open or epoxy filled

D. Electrode: fired on silver/frit

Figure 2.1. Design of 3-1 and 3-2 perforated block composite transducer.

2.1.1 Materials:

UPI PZT 501 A

Monsanto Gelvatol type 20-30 (PVA)

Distilled water

(See Appendix B for suppliers)

2.1.2 Procedure

Batch 10 gm of 20 wt% PVA in aqueous solution per 150 gm PZT powder in a plastic ball mill jar. Knead the mixture with a spatula until it is uniformly dampened by the binder solution (1-3 min). Seal the jar and place it on a ball mill for 18 hours (no media). The mixture should resemble a clay-like pug. More PVA solution may be added on a drop by drop basis to adjust pug rheology depending on the cross section area of the extrusion tip. This step is more art than science.

The pug is homogenized and de-aired in a device especially designed at MRL. It consists of two stainless steel ram and die sets clamped together with a perforated separator plate. The pug is chopped in 1/4 inch pieces and placed in one chamber. A port in this chamber allows a vacuum to be drawn on the whole assembly. O-rings hold the vacuum once drawn. The ram is allowed to compress the pug under vacuum pressure. The assembly is placed in a holder on a carver lab press and the pug is alternately forced from one chamber to the other through the perforated plate. A minimum of 20 cycles was used. This device is probably not as good as a conventional pug mill used in the brick and ceramics industry, but such a unit that would accept laboratory size batches could not be found.

Extrusion is done using a ram and die set mounted on a hand operated Enerpac hydraulic press. A variety of extrusion tips may be attached to the front of the die. The pug is packed carefully into the die to avoid air

pockets and the ram is inserted (a teflon o-ring prevents back flow of the pug). The extrusion rate is controlled by operator pressure or a hand-lever intensifier so that the extrusion rate matches the speed of the moving glass carrier which accepts the extruded shape.

The 3-1 shape is extruded from a tip with a square hole in which is mounted a round center-pin. The square hole and pin are sized to allow for drying and firing shrinkage (about 15%). Square tubes are dried 18 hours then cut to short lengths with a razor knife. At this point the 3-2 shape may be fabricated by drilling a series of evenly spaced holes in the green ware (allowing for shrinkage and cutting).

Except in the earliest trial arrays, the extruded 3-1 shape was not used. The extrusion method employed at MRL is very primitive. The pug was difficult to de-air properly as evidenced by large pores in the fired part. The pug was far from being homogeneous as evidenced by changes in extrusion rate while applying even pressure and twisting of the extruded tube. The problem of slumping on the carrier prior to drying was attacked but never completely solved.

These problems can be dealt with easily by any capable ceramic extrusion operation through the use of high shear mixers, de-airing pug mills, and automatic temperature controlled extruder heads with thermosetting binders.

Alternatively, the 3-1 shape and perhaps the 3-2 shape could be fabricated by injection molding. Either of these techniques could be cost efficient production methods. The primary difficulty with the extruded 3-2 elements lies in the poling operation which was always more difficult (in terms of high voltage, breakdown) with these parts. For practical reasons, it is more efficient for us to pole the bulk ceramic and then drill the 3-1 and 3-2 shape. There is some indication by A. Safari of our Lab, who developed

this shape, that poling is less effective when performed on elements that have already been drilled.

Since the extrusion process uses conventional PVA binder, the parts can be burned out and fired as described in Section 2.2.

2.1.3 Element Statistics

Early in the work after a significant number of 3-1 extruded elements had been prepared and sorted, a count was taken of the number of elements falling in various d_{33} ranges. The distribution of values is shown in Figure 2.2. The mean value for all samples was 378.0 pC/N and the standard deviation was 45.7 pC/N.

2.2 Fabrication of 3-1 and 3-2 Elements by Ultrasonic Machining

The first 3-1 and 3-2 transducer elements were produced by diamond sawing of PZT pellets to form blocks. This was followed by ultrasonic drilling to form the perforation. When optimization of the extrusion process with equipment available at MRL failed to improve individual elements, the machining method was resumed. The time involved with this procedure is very high on a per part basis since each individual element is cut slowly from the ceramic. Because this element type has the best collection of properties (high permittivity, high sensitivity, durability, etc.) and because easy production is envisioned, more effort was spent in fabricating arrays with this element. This is the reason for the great number of man-hours invested in the work to date.

2.2.1 Materials

UPI PZT 501 A

Monsanto Gelvatol Type 20-30 (polyvinyl alcohol-PVA)

DuPont Silver Frit Electrode #7095

Figure 2.2. Piezoelectric coefficient statistics for extruded 3-1 transducer elements (open perforation).

FREQUENCY PERCENT

d_{33} Upper Limit (pC/N)	1 2 3 ----0----0----0		Frequency %	Element Count
290			0.00	0
310	*		1.22	3
330	**		3.27	8
350	*******		14.69	36
370	*************		26.53	65
390	***********		22.45	55
410	**********		20.41	50
430	*****		11.93	28
		Total	100.00	245

Hammond Litharge (PbO)

Harshaw Zirconia (ZrO_2)

Trabond 2113 Epoxy

Distilled Water

2.2.2 Procedure

PVA binder is prepared as a 20 wt% aqueous solution and mixed with PZT 501 A at 7 g per 100 g powder to prepare a 1.4 wt% binder mixture when dried. Mixture is prepared in large mortar and pestle and heated at 110°C for 10 minutes then ground. This procedure is repeated until the resulting mixture is completely dry and passes an 80 mesh sieve.

Pellets are pressed in a one-inch diameter steel die at 19 to 20 kilopounds/in^2. A die-fill of 12.5 gm gives a pellet of sufficient fired thickness to produce 4 mm high plates after grinding.

Binder is burned out at 300°C for 1.5 hours and 500°C for 1.5 hours in an open crucible on Pt foil. A lead source prepared from 180 gm PbO and 100 gm ZrO_2 is added to the crucible and it is sealed. Pellets are fired at 1285°C for 1.5 hours (heating rate 250°C/hr). Pellets are ground flat on 600 grit SiC paper (wet), then mounted on a flat steel plate using thermosetting cement. Samples are surface ground with an 80-grit diamond wheel to a thickness of 0.157 $\pm$ .001 inches. Pellets are then diamond sliced to give square bars of random length.

Bars are ultrasonically cleaned in acetone (2-3 min) prior to electroding. DuPont #7095 electrode suspension is hand-painted on opposing faces and allowed to air dry for 18 hours. The electrode is then fired on at 550°C for 10-15 min.

Electroded bars are poled at 110°C with a field of 22 kV/cm for 1 min. The d_{33} coefficient of each bar is measured (Berlincourt d_{33} meter) to check poling quality.

Bars are mounted on glass* ultrasonically drilled (Sheffield Cavitron, 0.109 inch O.D. drill bit) to form a series of carefully spaced perforations. Individual 3-1 element blanks are then diamond sliced from each bar. For the 3-2 element these cubes are remounted and drilled again. Cubes are measured to check proper sizing and centricity. Capacitance of each element is measured at one kHz using a Hewlett-Packard Model 4274A LCR meter. Elements with capacitance below 25 pf and loss greater than .05 are rejected. Piezoelectric coefficient is measured and elements with d_{33} values below 200 pC/N are rejected. Polarity is marked on each element and good parts are sorted by d_{33} range.

Satisfactory elements are chosen for use in hinged arrays. They are cleaned ultrasonically in hexane for 5 min (*extended cleaning has resulted in removal of the silver-glass electrode*). One side of the perforation is sealed with tape and the center hole is filled with Trabond 2113 epoxy. The material which fills the perforation has been the subject of several variations as can be seen in the data, but the epoxy filled hole seems to give the best results.

The hydrostatic voltage coefficient was measured on random elements using test equipment built at MRL. This consists of an oil filled cylinder in which the sample resides and in which the pressure can be increased at 50 psi/sec. A hydrostatic pressure is generated by a piezoelectric driver and the sample response is measured on a Nicolet 204A oscilloscope or a Hewlett-Packard 3585A Spectrum Analyzer. The hydrostatic voltage coefficient is calculated by

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*To prevent depoling, the temperature of thermobond cement should not exceed 350°C and parts should not be subjected to shock.

comparison to a known PZT standard measured at the same time. Acceptable values average near 14×10^{-3} Vm/N.

2.2.3 Element Variations

The 3-1 and 3-2 elements used in this study are PZT cubes that have either one or two orthogonal perforations in them. These elements may be incorporated into the flexible array in such a way that the holes are either unfilled, filled by the matrix, or filled with other materials.

The unfilled state is achieved by packing the holes with alumina fibers. This prevents the matrix material from intruding into the holes during the casting operation, but does not give physical support to the interior of the element in the cured matrix. Neither does it prevent matrix material from straining into the hole when the array is subjected to high pressure. Wooden rods were inserted to simulate a non-reinforcing non-intrusion situation.

Alternately, the hole can be left open and filling can occur by whatever matrix compound is used. Finally, the hole may be filled with a material that bonds to the PZT, but is different from the matrix material. Two variations were prepared, 1) the SPURRS epoxy that was used in the developmental research of this composite, and 2) Trabond No. 2113 epoxy, a hard epoxy similar in cured properties to the SPURRS system, but with higher viscosity in the uncured state.

1''x1'' array tests have shown that the epoxy filled elements give the best results of the variations attempted. The Trabond #2113 is easier to use in filling the cubes without leakage and this method was chosen for the large arrays.

2.3 Fabrication of 1-3-0 PZT Rod Composite Elements

This element has the highest sensitivity and the lowest permittivity of the three basic element types used in this project. It is fabricated by

alligning PZT rods in a polymer matrix and poling parallel to the length of the rod. Microballoons are added to the polymer to control density and increase polymer compliance without pressure dependence. Two variations on this element were considered, one using .012'' diameter rods spaced to give 7.3 volume percent PZT and .018'' diameter rods spaced to give 9.2 volume percent PZT. The design of these elements is shown in Figure 2.3.

2.3.1 Materials

UPI PZT 501 A

REN Epoxy Resin

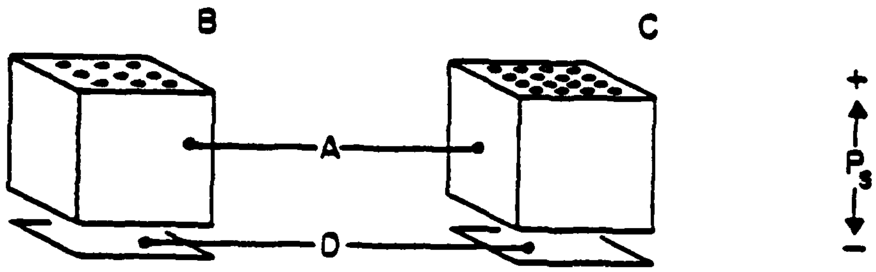
Emerson and Cummings Microballoons Grade IG-25

ACME E-Solder #3021 Epoxy Electrode Paste

2.3.2 Procedure

PZT rods with fired diameters of 12 and 18 mil (.0305 and .0457 cm) are prepared by extrusion as described in Section 2.2 followed by burn-out and firing as described in Section 2.1. Rods are inspected for straightness, roundness and porosity defects prior to use. Rods are inserted in a rack which aligns them to the proper array spacing. The 12 mil rods are aligned on a 0.1 cm center-to-center spacing (0.05 cm boarder) in a 4x4 array. This gives 7.30 volume percent PZT in a 0.4 cm cube. The 18 mil rods are aligned on a 0.133 cm center-to-center spacing (0.067 cm boarder) in a 3x3 array. This gives 9.23 volume percent PZT in the finished 0.4 cm cube. Two rod arrays are available in each rack. After loading the rack, it is inserted in a slotted teflon block and sealed with silicon rubber cement.

The REN epoxy mixture is prepared following manufacturers directions (no foaming agent) and 50 volume percent microballoons is added. This mixture is



A Composite Block: Epoxy/50 vol %/microballoons (4 x 4 x 4 mm)

B PZT Rods: 18 mil diam. x 4 mm

C PZT Rods: 12 mil diam. x 4 mm

D Electrode: Silver Loaded Epoxy

Figure 2.3. Design of 1-3-0 PZT rod composite transducer.

poured into the racks to fill and surround the rods and then cured 18 hours at 70°C.

After curing the composite blocks are pried from the teflon mold. The end plates of the rack are removed by diamond slicing. The block is inserted in a milling machine and excess filler is removed using a carbide tipped flycutter. The resulting block is sliced down the center to separate the two arrays and the remaining dimensions are sized. The resulting 0.4x0.4x2 cm rods are thermobonded to glass and 0.4 cm cubes are diamond sliced from them.

The resulting cubes are electroded on the faces with exposed rods using Acme E-solder silver/epoxy electrode and cured at 70°C for 18 hours.

Elements are poled at 80°C, 22 kV/cm for 2 min. They are then cleaned in a solution of DI water and 'Joy' liquid detergent in an ultrasonic bath for 2-3 min. They are rinsed with DI water and wiped with a cloth soaked in ethanol.

Each element is checked for proper rod alignment, size (0.4 mm cube) capacitance and loss (greater than 3.0 pf and less than 0.05 respectively), and piezoelectric d_{33} coefficient (150-400 pC/N). Random elements are checked for proper hydrostatic voltage coefficient (gh). Acceptable values averaged around 50×10^{-3} Vm/N.

2.3.3 Element Statistics

When a reasonable number of 1-3-0 composite elements had been fabricated and sorted by d_{33}, a count was taken for each d_{33} range. The distributions for 12 mil and 18 mil rods are shown in Figures 2.4 and 2.5. For 12 mil rods the mean was 230.0 pC/N with a standard deviation of 28.1. For 18 mil rods the mean was 221.6 pC/N with a standard deviation of 33.0.

When the normal d_{33} measurement is performed on these samples, the value measured can vary depending upon whether the probe is aligned directly over a

Figure 2.4. Piezoelectric d_{33} coefficient statistics for 1-3-0 composite transducer with 12 mil rods.

FREQUENCY PERCENT

d_{33} Upper Limit (pC/N)	1 2 3 4 ——0——0——0——0	Frequency %	Element Count
150		0.00	0
170	*	2.44	1
190	**	4.88	2
210	***********	21.95	9
230	*************	26.83	11
250	****************	31.71	13
270	*	2.44	1
290	*	2.44	1
310	****	7.32	3

Figure 2.5. Piezoelectric d_{33} coefficient statistics for 1-3-0 composite transducers with 18 mil rods.

FREQUENCY PERCENT

d_{33} Upper Limit (pC/N)	1 2 3 ----0----0----0	Frequency %	Element Count
150		0.00	0
170	*	2.67	2
190	******	12.00	9
210	*************	25.33	19
230	*************	26.67	20
250	*********	17.33	13
270	***	5.33	4
290	***	5.33	4
310	***	5.33	4

PZT rod or not. The 18-mil rod composite with only 9 rods per block is most sensitive to probe placement. Five samples were taken from a group with measured d_{33} ranging from 210 to 230 pC/N and measured carefully at five locations from the center of the block to a corner on both the positive and negative face. The results are shown in Table 2.1. The results show that the measurement variation in probe placement still lies within the boundaries of the sorted group.

2.4 Fabrication of 3-3 BURned-Out Plastic Sphere (BURPS) Composite

The BURPS composite has moderate sensitivity and permittivity. Except for the critical burn-out step, it is the easiest to prepare since it follows conventional powder processing and pelletizing techniques. The final machining of these parts is simple and easily automated. This is the easiest of the three elements to scale up for mass production. Indeed it is already being manufactured in Japan. It consists of a three dimensionally connected intermix of PZT and polymer. It is formed by mixing PZT powder with plastic spheres/pelletizing, burning out the spheres to give a large 3-d connected porosity, sintering the PZT and finally vacuum impregnating the porous PZT with a low viscosity hard polymer and poling. A schematic of the basic structure of this transducer is shown in Figure 2.6.

2.4.1 Materials

UPI PZT 501 A

PolyMethylMethacrylate (PMM) Spheres (Polysciences #4553)

SPURRS Low Viscosity Embedding Epoxy (Polysciences #1916)

ACME 3021 E-Solder

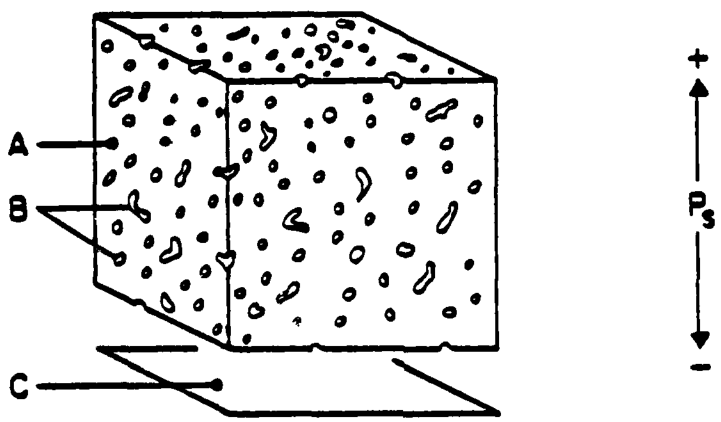
2.4.2 Procedure

Batch 100 gm PZT and 20 gm PMM spheres. Ball mill dry with zirconia media 18 hours. Add 5.010 gm of 20 wt% PVA solution (see Section 2.1), work

Table 2.1. Piezoelectric d_{33} coefficient as a function of probe position for 1-3-0 composite transducers with 18 mil rods

Piezoelectric d_{33} (pC/N)							
	Position						
Sample	a	b	c	d	e	Mean	S.D.
1+	209	208	231	243	207	220	16
1-	244	212	236	206	248	229	19
2+	190	196	205	199	183	195	8
2-	216	214	228	214	227	220	7
3+	187	214	190	274	199	213	36
3-	203	191	223	196	230	209	17
4+	181	246	203	190	208	206	25
4-	202	272	269	218	228	238	31
5+	194	179	216	238	231	212	25
5-	247	192	285	257	270	250	36

a = center rod, e = edge of composite (previously measured with d_{33} ranging from 210 to 230 pC/N).



A PZT Block 4 x 4 x 4 mm

B Burned-out Plastic Spheres Filled with Epoxy

C Electrode: Silver Loaded Epoxy

Figure 2.6. Design of 3-3 BURPS composite transducer.

with mortar and pestle until crumbly. Dry at 110°C for 10-20 min. Repeat grinding and drying until mixture is dry and passes through 60 mesh screen.

Add 5.010 gm of 20 wt% PVA solution per 100 gm of mixture. Repeat grinding and drying and sieving procedure.

Using a 1 inch diameter die and an 11 gm die-fill, press pellets at 15,000 psi (experiments prove this is the optimum pressing pressure for maximum d_{33}).

Place pellets in an open crucible on platinum setters and burn-out the binder using the following schedule with mild air flow.

Mode	Temp °C	Time (hr)	Rate (°C/min)
heat	ambient - 200	7	0.5
hold	200	10	0
heat	200 - 300	8	0.2
hold	300	10	0
heat	300 - 400	4	0.4
hold	400	5	0
cool	400 - ambient	furnace cool	

Seal crucible and sinter for 0.5 hours at 1285°C with $PbZrO_3$ lead source. After sintering pellets have a three dimensionally connected microstructure of PZT and porosity.

Pellet is placed in a standard capped sample ringform. A rough vacuum is drawn for 30 minutes and SPURRS low-viscosity epoxy (recipe B) is poured (under vacuum) to cover the pellet. Alternatively the sample may be covered with the epoxy mixture and then vacuum outgassed for 30 minutes. Epoxy impregnated pellet is cured at 70°C for 18 hours.

Excess epoxy is removed using a carbide tool on a conventional metal turning lathe. A special adjustable collet is used to hold the sample. Cutting continues until the top layer of PZT is removed. The sample is reversed and cutting continues until the proper sample thickness (0.4 cm) is achieved.

Square bars (0.4 cm) are cut from the pellets by diamond slicing with an 0.012 inch blade. Bars are electroded on the diamond sliced face (tests show better d_{33} in this orientation) with ACME 3021 E-solder and cured 18 hours at 70°C. Bars are poled at 80°C and 22 kV/cm for 5 min. Piezoelectric d_{33} coefficient is checked to insure proper poling.

Bars are diamond sliced to give 0.4 cm cubes. The cubes are cleaned with liquid detergent (Joy brand) solution in an ultrasonic bath for 1-3 min., then rinsed in DI water. Other solvents are not recommended since they seem to attack the SPURRS epoxy.

Cubes are checked for proper physical dimensions. Capacitance and loss are measured and elements with capacitance lower than 8.0 pf or loss greater than 0.05 are rejected. The piezoelectric d_{33} coefficient is measured with acceptable values ranging from 180 to 235 pC/N. The hydrostatic voltage coefficient is checked on several samples from each lot. Acceptable values average around 18.00×10^{-3} Vm/N.

3.0 Fabrication of Conformal Arrays

The fabrication of conformal arrays requires four basic operations. The individual elements must be assembled in proper geometrical alignment in such a way that they do not move about. The flexible matrix material must be cast around the elements in such a way that it is void free. A flexible electrode must be applied that integrates the transducers into a single electrical unit with attachment to the outside world. Finally, the whole device must be potted into a flexible jacket that seals the unit against intrusion of fluid at high pressure (see Figure 3.1).

As first envisioned, this seemed a simple task. Earlier work with polyurethane showed that it could be used as a flexible hinge that gave sufficient bonding to ceramic and polymer composites. Its high tensile strength, elasticity and abrasion resistance gave it precedent over other candidate materials. It is hydrostatically incompressable (Poisson ratio near 0.5) which causes hydrostatic pressure to be transmitted to the sides of the elements and, under pressure, becomes acoustically hard. It was felt, however, that a small interelement spacing would alleviate the problem. A polyurethane based conductive material was available commercially and it was agreed that the body of the work on this project would consist of making elements in large numbers followed by simple assembly of the arrays.

Unfortunately, polyurethane (at least the commercial formulation we have worked with) did have some drawbacks. The interelement spacing chosen (0.074", 0.188 cm in 16 element 1"x1" arrays) was perhaps insufficient to isolate the element sides from transverse stress, since the observed g_h was often lower than that shown by single elements. Further, this polyurethane does not bond very well to ceramic or other polymeric surfaces. Although it is possible that coupling agents may improve this, cursory work was not immediately encouraging.

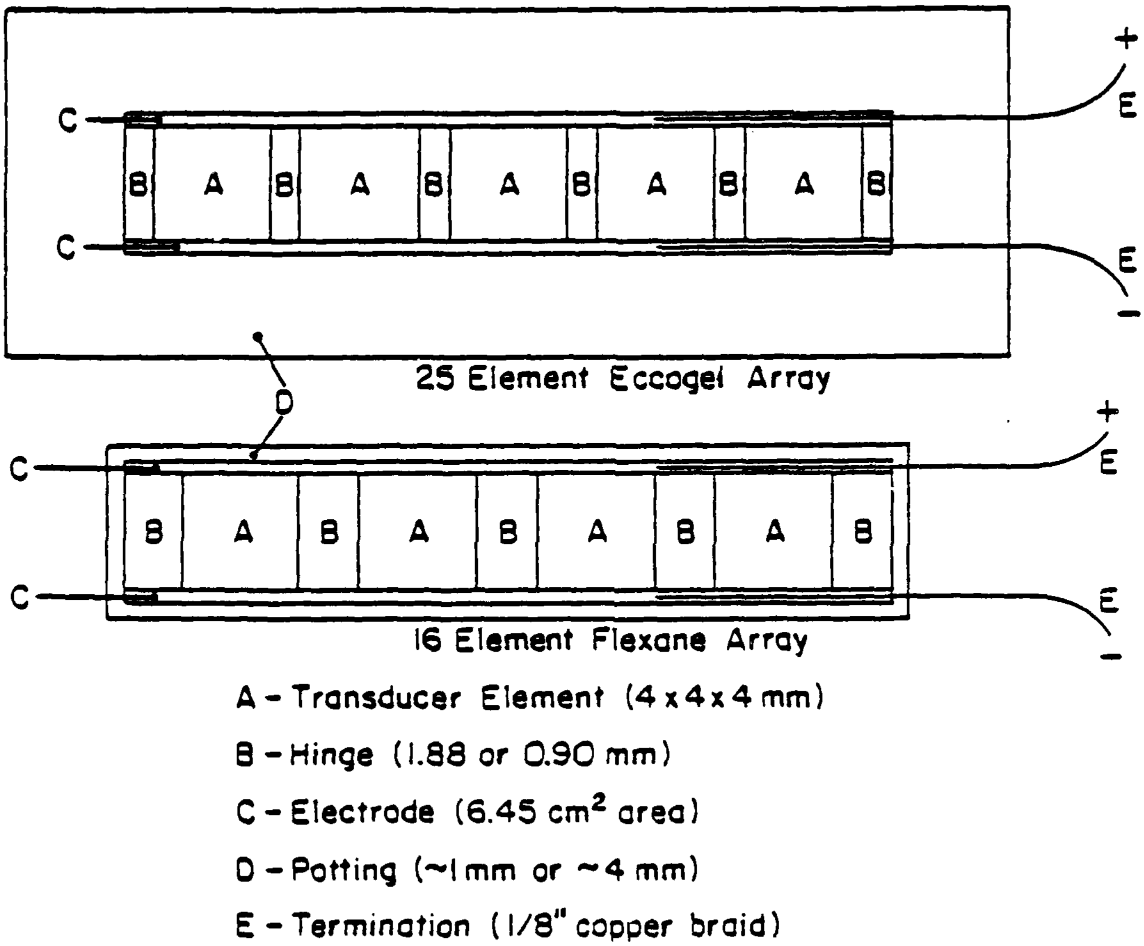


Figure 3.1. Design of conformal arrays.

It would also seem to be a characteristic of polyurethanes that they do not bond well to a previously cured polyurethane surface. This makes the potting layer very difficult to apply with confidence that external fluids will not penetrate the jacket/matrix interface.

Finally, the commercial polyurethane-based flexible electrode that was chosen when this unit was proposed was found to have insufficient electrical conductivity in subsequent testing. Further surveys did not reveal a commercially available alternative material. A sufficiently conductive flexible electrode was developed by us for use on the polyurethane arrays, but it employs a carbon fiber conductive filler which also acts to reinforce the elastomer and degrade its flexibility somewhat. This is not completely undesirable since a somewhat stiffer cover layer over the matrix appears to enhance the longitudinal stress and so increase the g_h of the device.

3.1 Element Assembly

A square sheet is cut from card stock and the array lined out. For the majority of the arrays, the hinge thickness between elements was 0.188 cm with the same boarder (4x4 array - 1'' square device). In an attempt to improve the sensitivity of the device, several have been made with 0.090 cm hinge and boarder (5x5 array - 1'' square device).

Elements are visually aligned and glued in place with Evan's Welsh Glue. This glue softens slowly in warm water allowing the card stock to be removed after casting. Elements are placed electrode down, all in the same polarity. In the case of the 3-1 elements, the orientation of the central hole is rotated 90° for adjacent elements.

3.2 Casting of Hinging Matrix

The array is placed in a metal box-mold with removable side plates. The matrix polymer is prepared and poured into the mold to cover the elements.

Care is taken to remove visible bubbles from the liquid. A polypropylene sheet with overflow port is placed on top of the array, then a rigid metal plate (same overflow port location) is slowly pressed into the mold and excess polymer is forced out. The polymer is cured at 70°C for 18 hours. The mold is disassembled and flashing is trimmed off. Finally, the array is soaked in warm water and the card stock is peeled away.

All excess glue is carefully scrubbed from the electrode faces on the card stock side. Excess polymer is cut from the electrodes of the opposite side. The array is washed in ethanol to remove any chemical residue or oils from the surfaces.

Two distinct families of matrix (hinge) material have been investigated. The first is polyurethane. The material used in this study is known commercially as Flexane and is manufactured by Devcon Corporation, Danvers, MA. Originally it was supplied in 4 distinct hardnesses 30, 60, 80, and 94. Of these, 30 and 60 had sufficient flexibility for our application. This material is now supplied only as Flexane-80 with an additive for use in preparing the more flexible compositions.

The second material is a flexible epoxy known as Ecco-gel supplied by Emmerson and Cummings, Inc., Canton, MA. It is also available in a variety of durometers. We have investigated 0, 25, 45 and 80. In general, flexibility decreases with increasing durometer.

3.3 Application of Flexible Electrode

The flexible electrode compound is painted onto both faces of the array approximately 1/16 inch thick. Cleaned wire mesh leads are embedded into the electrode. The electroded array is sandwiched between polypropylene sheets then metal plates and clamped, then cured at 70°C for 18 hours. After curing, any excess electrode is trimmed along the edge of the array.

Two separate electrode systems were developed for use on conformal arrays. A variety of materials were investigated as conductive fillers for polyurethane, including silver powder, carbon black, flake graphite and carbon fiber. It was found that Thornel VME grade carbon fiber from Union Carbide Corporation, Chicago, IL, at 45% wt loading in Devcon 30 durometer flexane polyurethane gave the best results in terms of workability and resistivity. Silver loaded polyurethanes were examined but the full range of available particle morphologies were never tested in polyurethane. The optimum electrode system is dependent on particle size, particle shape and volume percent loading of the filler. The conductive filler must achieve some degree of long range physical cross linking to achieve good conductivity, and when this occurs the viscosity of the mixture and the rigidity of the cured electrode can increase dramatically. It is likely that a mixture of particle shapes is the most desirable with some providing long range conduction and some providing short range contact in three dimensions. The carbon fiber electrode is applied and then pressed out to achieve a thin layer with a high degree of cross linking.

For the flexible epoxy arrays, a different filler system worked best. A 4:1 mixture of Metz I-200 fine silver powder and Metz #16 silver flake at a 13.7 vol% loading in Eccogel 0 durometer flexible epoxy gave optimum results for conductivity, flexibility and strength. Carbon fibers were tried in Eccogel, but the optimum loading gave a much lower conductivity. This electrode is also applied with a pressing step before curing.

In both cases, the electrical connections are included in the application of the flexible electrode. The best connection was found to be copper braid sold for desoldering application (no flux). This made a durable, flexible contact to the outside and was held strongly by the flexible conductive layer.

3.4 Potting of Conformal Arrays

Two different potting techniques have been used for arrays depending upon the polymer systems used for the matrix and the flexible electrode.

For polyurethane arrays, the potting material is Flexane #30 durometer. This is mixed and the array is dipped several times until the mixture thickens with room temperature curing and a heavy coating is built up that completely covers the array and leads. This is then placed on a polypropylene sheet and cured at 70°C for 18 hours.

For epoxy arrays, the potting will adhere to itself better than with the polyurethane. In this case, the array is suspended in a mold and held centered by small blocks of cured potting material. More potting compound is prepared and poured around the array and leads. The potted array is cured at 70°C for 18 hours.

4.0 Testing of 1''x1'' Conformal Arrays

Prior to assembly, all elements are tested for capacitance using an HP 4742A LCR meter and sorted on a pass/fail basis. All devices are tested for piezoelectric d_{33} coefficient using a Berlincourt meter. Elements showing better than pass/fail values are sorted into lots and marked for polarity. Selected elements that pass the above tests are tested for hydrostatic voltage coefficient. The equipment for this determination is shown in Figure 3.1. the sample is immersed in an oil filled cylinder and its response to A.C. stress compared to a standard with known g_h. Either a Nicolet 204A oscilloscope or an HP 3585A spectrum analyzer is used to measure the output signal at pressures from zero to 1000 psi. Average characteristics for accepted elements are listed in Table 3.1.

All arrays fabricated in the 1''x1'' size have been tested for capacitance on the HP 4742A and for hydrostatic voltage coefficient in the apparatus of Figure 4.1. Results are compared in the following tables. Capacitance and g_h are used to calculate d_h using the electrode area of the device. Sensitivity referenced to 1 volt/μPa is calculated from the measured g_h at 100 and 1000 psi. Comparison of these values will give a rough idea of the pressure dependence of the devices. The k_{33} shown in these tables is based on the electroded plate area of the entire array. The piezoelectric coefficient is the mean value for all elements included in the array. Complete data for arrays at all pressures tested both before and after pressure cycling and data for comparison of total element electrode area values and device area values is collected in Appendix A.

Table 4.2 shows characteristics of 16 element flexible arrays prepared from 3-1 elements with neat (unfilled, unfoamed) matrix. Sample FLEX 20 was the first array made on this project and its values appear to be anomalously

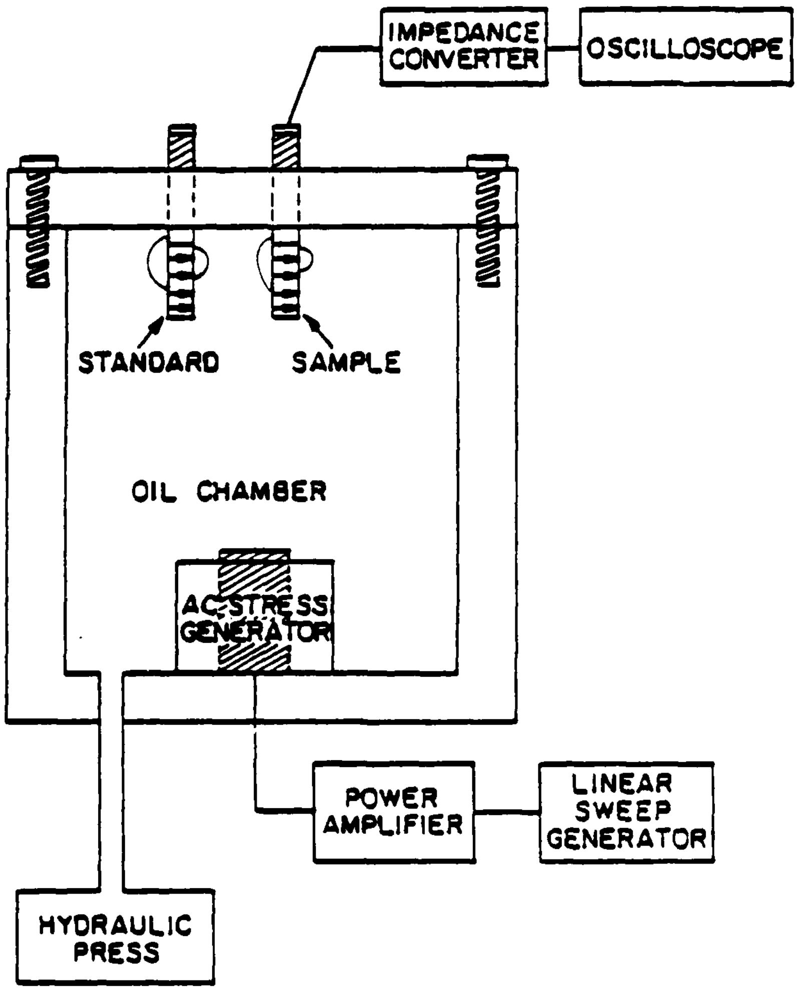


Figure 4.1. Apparatus used for dynamic A.C. measurement of hydrostatic voltage coefficient.

Table 4.1. Average Acceptable Characteristics of Individual Transducer Elements.

Type	Density (gm/cm^3)	Capacitance (pF)	Loss D	k_{33}	d_{33} pC/N	$\bar{g}_h$ Vm/N	$\bar{d}_h$ C/N	$g_h d_h$ m^2/N
Ext. 3-18*	5.6866	25.0	0.05	700	150-400	14	86.8	1215
Mach. 3-1*	5.6866	25.0	0.05	800	150-400	14	99.2	1388
1-3-0 (12 mil rod)	1.4894	3.0	0.05	85	150-390	50	37.6	1881
1-3-0 (18 mil rod)	1.4387	3.0	0.05	85	150-450	50	37.6	1881
3-3 BURPS	4.6559	8.0	0.05	250	180-280	18	39.8	717

*Epoxy filled perforation.

Table 4.2. Properties of Polyurethane Based, 16 Element Arrays, 3-1 Element Type, Neat Matrix.

Device No.	Element Description	Matrix No.	Properties at 100 psi				S 1 kpsi db: V/μPa	k_{33} (Device)	d_{33} (Mean) pC/N
			g_h Vm/N	d_h C/N	$g_h d_h$ m^2/N	S db: V/μPa			
FLEX 21	Ext, Packed	30	11.4	33.5	382	-207	--	332	400
FLEX 20	Ext, Packed	60	24.5	82.6	2027	-200	-201	380	420
FLEX 22	Ext, Packed	60	13.8	46.0	632	-205	-206	377	420
FLEX 28	Ext, Packed*	60	12.8	38.3	492	-206	-210	337	360
FLEX 35	Mach, Epoxy Fill	60	21.6	74.2	1602	-201	-202	389	313

*Conventional electrode and chopped silver wire.

high. Perhaps this is because of its very thick, stiff carbon fiber/ polyurethane electrode. FLEX 21-28 all contain extruded 3-1 elements. The 3-1 perforation was packed with fiber frax but not sealed against matrix intrusion during forming. From tests on individual elements, it is certain that completely filling the perforation with a hydrostatically incompressable material like polyurethane will nearly destroy the hydrostatic response, since the pressure inside the perforation becomes equal to the pressure applied in the 3-direction. On this basis, and neglecting the data of FLEX 20, sample FLEX 35 which is prepared from machined 3-1 elements in which the perforation has been filled with epoxy represents a dramatic improvement. It also appears from this data that the harder flexane 60 devalues the g_h response less than the softer flexane 30.

Data in Table 4.3 is for 16 element arrays in which the matrix has been foamed by adding water to the mix before curing. This technique enhances the low pressure g_h values especially for the *30 durometer flexane* (which also foams better), but results in an extremely pressure dependent device. See Appendix A for plots of g_h vs pressure. Foaming the matrix can enhance the g_h value of the array (above that measured for individual elements) at low pressure because the carbon fiber loaded electrode is stiffer than the matrix and enhances the 3-direction stress of the device. This effect disappears as the foamed matrix presumably collapses at higher pressures and stress is transmitted through the matrix in the transverse direction.

Pressure dependence also occurs (but to a lesser extent) in the microballoon and PMM (Polymethylmethacrylate spheres) filled matrices of Tables 4.4 and 4.5 respectively. The properties of arrays with a PMM filled matrix are, in general, superior to those with microballoon filler: higher g_h, $g_h d_h$ product and sensitivity. They also have slightly lower pressure dependence. If we assume that microballoons can implode at high pressure,

Table 4.3. Properties of Polyurethane Based, 16 Element Arrays, 3-1 Element Type, Foamed Matrix.

Device No.	Element Description	Matrix %	Properties at 100 psi				S 1 kpsi db: V/μPa	k_{33} (Device)	d_{33} (Mean) pC/N
			g_h Vm/N	d_h C/N	$g_h d_h$ m^2/N	S db: V/μPa			
FLEX 24	Ext, Packed	30	27.8	82.5	2293	-199	-206	335	380
FLEX 40	Mach, Epoxy Fill	30	26.3	88.3	2322	-199	-203	380	265
FLEX 23	Ext, Packed	60	13.8	46.0	632	-205	-207	377	420
FLEX 34	Mach, Epoxy Fill	60	14.6	36.0	526	-204	-207	278	276

Table 4.4. Properties of Polyurethane Based, 16 Element Arrays, 3-1 Element Type, Microballoon Filled #30 Matrix.

Device No.	Element Description	Vol % Filler	Properties at 100 psi				S 1 kpsi db: V/μPa	k_{33} (Device)	d_{33} (Mean) pC/N
			g_h Vm/N	d_h C/N	$g_h d_h$ m^2/N	S db: V/μPa			
FLEX 26	Ext, Packed	40	9.6	27.9	268	-208	-211	330	360
FLEX 33	Ext, Epoxy Fill	40	13.3	39.7	528	-205	-206	337	342
FLEX 29	Ext, Packed	55	14.7	32.8	481	-205	-208	252	360
FLEX 39	Mach, Epoxy Fill	55	38.4	128.0	4913	-196	-204	377	313

Table 4.5. Properties of Polyurethane Based, 16 Element Arrays, 3-1 Element Type, PMM Filled #30 Matrix.

Device No.	Element Description	Vol % Filler	Properties at 100 psi				S 1 kpsi db: V/μPa	k_{33} (Device)	d_{33} (Mean) pC/N
			g_h Vm/N	d_h C/N	$g_h d_h$ m^2/N	S db: V/μPa			
FLEX 30	Ext, Packed	40	16.4	51.3	839	-203	-208	354	380
FLEX 31	Mach, Epoxy Fill*	40	26.9	61.7	1660	-199	-203	259	424
FLEX 32	Mach, Epoxy Fill	40	41.5	103.3	4288	-195	-198	281	383
FLEX 38	Mach, Epoxy Fill**	40	21.1	70.5	1485	-201	-201	378	313
FLEX 37	Mach, Epoxy Fill	35	23.7	78.4	1855	-200	-203	374	365

*4 at 4 hole bars.
**Eccogel/silver electrode.

then PMM filler should also be more reproducable. Both the PMM and microballoon filled arrays are superior in pressure dependence to the foamed arrays.

The next three tables list data for arrays prepared from epoxy based elastomers sold commercially as Eccogel 1365 of varying hardness. Table 4.6 presents a series of devices prepared to investigate the effect of elastomer durometer variations in both the matrix and the sealing jacket (which for these devices is quite thick) on the hydrostatic properties of the device. The data is confused perhaps because (as with the flexane arrays) individual elements could not be generated in numbers sufficiently large to ensure uniformity (see mean d_{33} characteristics) from device to device. There appears to be a slight tendency for devices with harder (higher number) matrix to have higher hydrostatic voltage coefficient and less pressure sensitivity. One might expect that samples with a hard jacket and soft matrix the sensitivity of the array would be lower but this cannot be proven by the data.

Table 4.7 shows data from three devices prepared with some of the same matrix variations as Table 4.6 but with 25 elements in the 1"x1" array. This reduces the hinge width from 0.188 cm to 0.090 cm and increases the d_h, $g_h d_h$ product, and permittivity of the device but has no effect on the hydrostatic voltage coefficient. These arrays are somewhat less flexible than for those with 16 elements per square inch, but are still within the proposed specifications. Flexing the 25 element array appeared not to overstretch and so disrupt the flexible electrode.

Table 4.8 shows data for two arrays with microballoon and PMM fillers in the matrix. It is more difficult to prepare a filled epoxy matrix material than is the case for the polyurethane because of the lower viscosity of the mix and longer pot life. The fillers tend to separate easily either floating or sinking depending on their density. The results show that filler addition

Table 4.6. Properties of Flexible Epoxy Based, 16 Element Arrays, Machined, Epoxy Filled 3-1 Elements, Neat Matrix.

Device No.	Matrix Type	Jacket Type	Properties at 100 psi				S 1 kpsi db: V/μPa	k_{33} (Device)	d_{33} (Mean) pC/N
			g_h Vm/N	d_h C/N	$g_h d_h$ m^2/N	S db: V/μPa			
ECCO 01	0	0	26.5	90.2	2392	-199	-201	384	265
ECCO 02	25	0	27.5	91.1	2505	-199	-201	374	265
ECCO 03	0	25	18.8	59.1	1111	-202	-206	355	313
ECCO 04	25	25	17.0	51.5	875	-203	-205	341	365
ECCO 05	45	25	28.2	94.8	2673	-199	-200	380	365
ECCO 06	80	25	30.5	99.7	3036	-198	-199	370	350
ECCO 07	0	45	25.2	84.6	2132	-200	-202	379	280
ECCO 08	25	45	25.2	82.4	2072	-200	-202	370	363
ECCO 09	45	45	29.6	97.2	2875	-199	-200	371	350
ECCO 10	80	45	26.9	90.2	2422	-199	-200	379	265

Table 4.7. Properties of Flexible Epoxy Based, 25 Element Arrays, Machined, Epoxy Filled 3-1 Elements, Neat Matrix.

Device No.	Matrix Type	Jacket Type	Properties at 100 psi				S 1 kpsi db: V/μPa	k_{33} (Device)	d_{33} (Mean) pC/N
			g_h Vm/N	d_h C/N	$g_h d_h$ m^2/N	S db: V/μPa			
ECCO 11	0	25	27.4	150.5	4117	-199	-201	621	325
ECCO 12	25	45	29.9	162.3	4850	-198	-200	613	325
ECCO 13	45	45	30.7	161.8	4962	-198	-200	596	350

Table 4.8. Properties of Flexible Epoxy Based, 16 Element Arrays, Machined, Epoxy Filled 3-1 Elements, Filled #25 Matrix, #25 Jacket.

Device No.	Filler Type	Vol Percent Filler	Properties at 100 psi				S 1 kpsi db: V/μPa	k_{33} (Device)	d_{33} (Mean) pC/N
			g_h Vm/N	d_h C/N	$g_h d_h$ m^2/N	S db: V/μPa			
ECCO 14	PMM	30	27.8	90.1	2505	-199	-200	366	313
ECCO 15	MB	40	36.9	127.8	4719	-197	-201	391	265

increases the low pressure g_h coefficient, but (especially in the microballoon filled matrix) increases the pressure dependence.

Table 4.9 reviews polyurethane and epoxy elastomer arrays prepared from 1-3-0 rod-composite elements. These elements are more time consuming to prepare than the 3-1 style transducer. These elements have a high intrinsic g_h and lower d_h but the product is higher than for the 3-1 elements. They also have a much lower capacitance (see Table 4.1).

Only in the case of FLEX 43 with its PMM-filled matrix does the g_h approach that of the individual elements but at higher pressure the value reduces to become equal to the other arrays. FLEX 42 appears to be anomalously low and the reasons for this are unclear.

The Eccogel arrays (16 and 17) are both prepared from elements (25 in a 1"x1" array) that are very similar in their piezoelectric characteristics. All responses of these two devices are essentially identical even though the matrix and jacket are of different hardness. This seems to indicate that the relative elastic properties of the elastomer is not very important for these types of elements. In fact this was expected because for the individual 1-3-0 elements the PZT rods (the active portion) are insulated from elastomer transmitted transverse stress by the epoxy/microballoon matrix.

Table 4.10 shows two Eccogel, 25 element arrays containing 3-3 BURPS elements. Only two arrays have been prepared from this transducer type because the properties seem to be the least favorable for the desired application. They have the lowest $g_h d_h$ produ f all the elements and moderate permittivity. In this case, the g_h value is the same in the array as for the individual elements. The elements were well matched and again no effect of elastomer durometer was seen with this array. The attractive feature of the 3-3 element is that it should be the easiest to put into mass production.

Table 4.9. Properties of 1-3-0 Rod-Composite Arrays.

Device No.	Rod Diam. (mil)	Matrix Type	Jacket Type	Properties at 100 psi				S 1 kpsi db: V/μPa	k_{33} (Device)	d_{33} (Mean) pC/N
				g_h Vm/N	d_h C/N	$g_h d_h$ m^2/N	S db: V/μPa			
FLEX 41[1]	12	FLEX 60	FLEX 30	31.9	12.5	398	-198	-198	44	230
FLEX 42[1]	18	FLEX 60	FLEX 30	9.4	4.8	47	-209	-208	58	200
FLEX 43[1]	18	FLEX 30-PM*	FLEX 30	45.3	24.8	1125	-194	-198	62	225
ECCO 16[2]	18	ECCO 25	ECCO 45	36.8	22.5	829	-197	-197	69	190
ECCO 17[2]	18	ECO 45	ECCO 25	36.3	21.3	772	-197	-197	66	182

1. 16 elements in 1''x1'' array.
2. 25 elements in 1''x1'' array.
* 40 vol% PMM in matrix.

Table 4.10. Properties of 3-3 BURPS Composite Arrays, 25 Elements in Flexible Epoxy

Device No.	Matrix Type	Jacket Type	Properties at 100 psi				S 1 kpsi db: V/μPa	k_{33} (Device)	d_{33} (Mean) pC/N
			g_h Vm/N	d_h C/N	$g_h d_h$ m^2/N	S db: V/μPa			
ECCO 18	25	45	18.2	38.2	696	203	203	238	208
ECCO 19	45	45	18.4	42.0	772	203	204	258	215

5.0 Devices Tested at Naval Labs

There is some complexity involved in describing the details of samples delivered for Navy testing. Some were sent to New London, some to Orlando, and one to Arlington. Some devices were numbered before shipment and others were not, all sample designations were reorganized recently when the data was stored on computer at MRL (FLEX and ECCO designations). Most shipments are documented with letters of transmittal but some now only by copies of data returned after Navy testing. Some of the present confusion occurred because the Principal Investigator, Dr. Walter Schulze, left MRL for a position at Alfred University. It is also true that no formal channels have been set up between MRL and Naval Labs for this work. Navy testing seems to have been conducted in a catch as catch can basis since there is no formal budget for this portion of work. This situation is not completely undesirable but perhaps helps to explain some of the confusion. However, our relations with Naval labs (especially with Dr. Robert Ting at Orlando) have been extremely productive.

5.1 Record of Sample Delivery

The following is a chronological record of delivered devices with new sample numbers for correlation with Appendix A.

November 5, 1982

Two samples were sent to C. LeBlanc at New London. Both were 1"x1", 16 element arrays with a No. 30 Flexane matrix containing 40 vol% PMM filler. One device contained 1-3-0 style transducers with 18 mil PZT rods (old designation: H2-29b-4, new designation: FLEX 43). The other device was prepared from machined 3-1 elements with epoxy filled perforations (old designation: H2-29b-5, new designation: FLEX 32).

We have only a telephone record of test data returned from New London.

It is our understanding that these devices were to be forwarded to Orlando for further testing, but according to Dr. R. Ting (personal communication) they did not arrive.

November 24, 1982

A large 4"x4" array containing 256 1-3-0 style elements in a No. 30 Flexane +35% PMM matrix was sent to Dr. Robert Pohanka in Arlington. After inspection, this was forwarded to Dr. Robert Ting in Orlando. This device was received but never tested, apparently due to jacket failure under pressurization. Old designation: LCA #1, no new designation, too large for testing at MRL.

December 21, 1982

A large 4"x4" array containing 256, 3-1 style elements (machined perforation) in No. 30 Flexane +35% PMM matrix was sent for testing to Dr. Robert Ting in Orlando. This device was tested and a copy of the results are included in this report. It was decided that all future devices would be sent directly to Orlando.

Spring 1982, (date unknown)

A 1"x1" array containing 16, 1-3-0, 12 mill rod elements with neat No. 60 Flexane matrix was sent to Orlando. The old sample designation was H2-17a-1, it is now listed as FLEX 41. This sample was tested and data and sample were returned to MRL.

Spring 1982 (date unknown)

Six polyurethane based arrays with different matrix composition were sent to Dr. Robert Ting in Orlando. All were prepared from machined 3-1 elements which had their perforations filled with epoxy. Dr. Ting plotted the MRL test data and copied this back to us showing his samples designations. They are shown below with their new numbers.

Orlando No.	New MRL No.	Matrix Composition
1	FLEX 35	No. 60 Flexane - neat
2	FLEX 36	No. 30 Flexane - neat
3	FLEX 37	No. 30 Flexane - 35 v/o PMM
4	FLEX 38	No. 30 Flexane - 40 v/o PMM
5	FLEX 39	No. 30 Flexane - 55 v/o Microballoon
6	FLEX 40	No. 30 flexane - foamed

Of these, only FLEX 37 (3) and FLEX 39 (5) were tested and data returned to MRL (samples retained in Orlando).

July 7, 1983

Three Eccogel epoxy based 1"x1" arrays prepared from machined 3-1 elements with epoxy filled perforations were sent to Orlando:

New MRL No.	Orlando No.	Array Description
ECCO 11	—	25 elements, No. 0 matrix, No. 25 jacket
ECCO 09	Eccogel 45/45	16 elements, No. 45 matrix, No. 45 jacket
ECCO 05	—	16 elements, No. 45 matrix, No. 25 jacket

Only ECCO 09 was eventually tested. In a subsequent letter from Dr. Ting (with data), it was reported that ECCO 11 and ECCO 05 were not tested because of visual inspection showed a matrix void and a misaligned element. All samples retained in Orlando.

5.2 Summary of Navy Test Data on MRL Conformal Arrays

Written data was received at MRL from Navy testing of five devices. Four of these were 1"x1" devices and the results may be compared to data obtained at MRL (see Appendix A). The other device was a 4"x4" array that was too large for testing at MRL.

Two devices were sent to the Navy Labs at New London, CT, c/o Charles LeBlanc. His comments were received by telephone only.

Old No.: H2-29b-4 (FLEX 43)   1-3-0, 18 mil rod, 16 elements

Capacitance: 85 pF, loss 8% at 1 KHz
Sensitivity: -192.5 dB from 1 KHz to 80 Hz then roll off
'damaging RC time constant'

Old No.: H2-29b-5 (FLEX 32)   3-1, epoxy filled, 16 elements

Capacitance: 391 pF, loss 4% at 1 KHz
Sensitivity: -196 dB from 1 KHz to 1 Hz

All measurements at room pressure.

USRD - Orlando

Test Data

on

Large Conformal Array No. LCA-2

MRL Description

Elements: 256 machined, epoxy filled, 3-1 elements

Matrix: #30 Flexane - 35 vol% PMM

Electrode: #30 Flexane - 45 vol% VME carbon fiber and chopped silver wire

Jacket: #30 Flexane - neat

Size: 4''x4'' with boarder

Electrode Area: 96.04 cm^2

Element Area: 40.96 cm^2

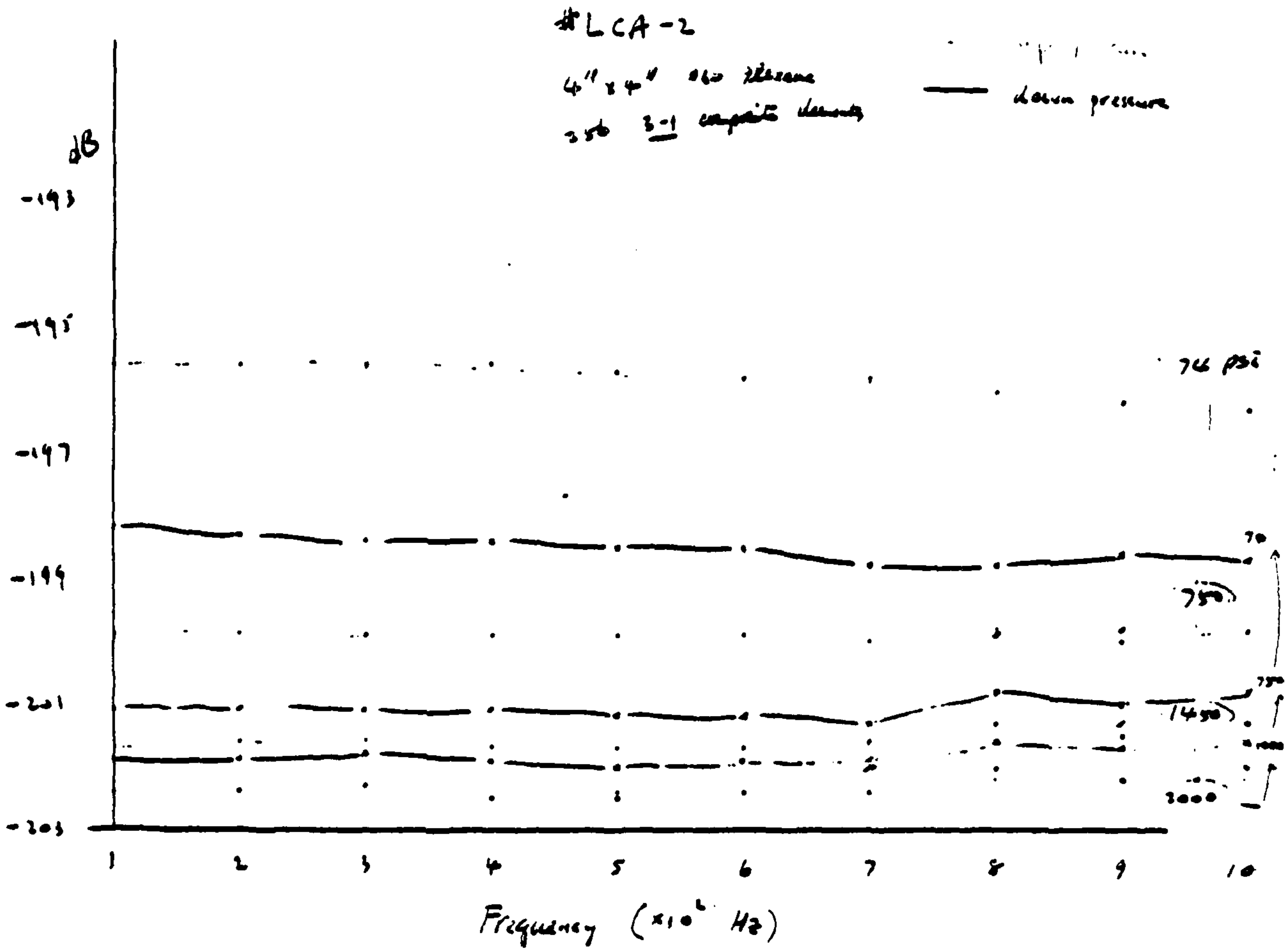
Capacitance: 8.07 nF

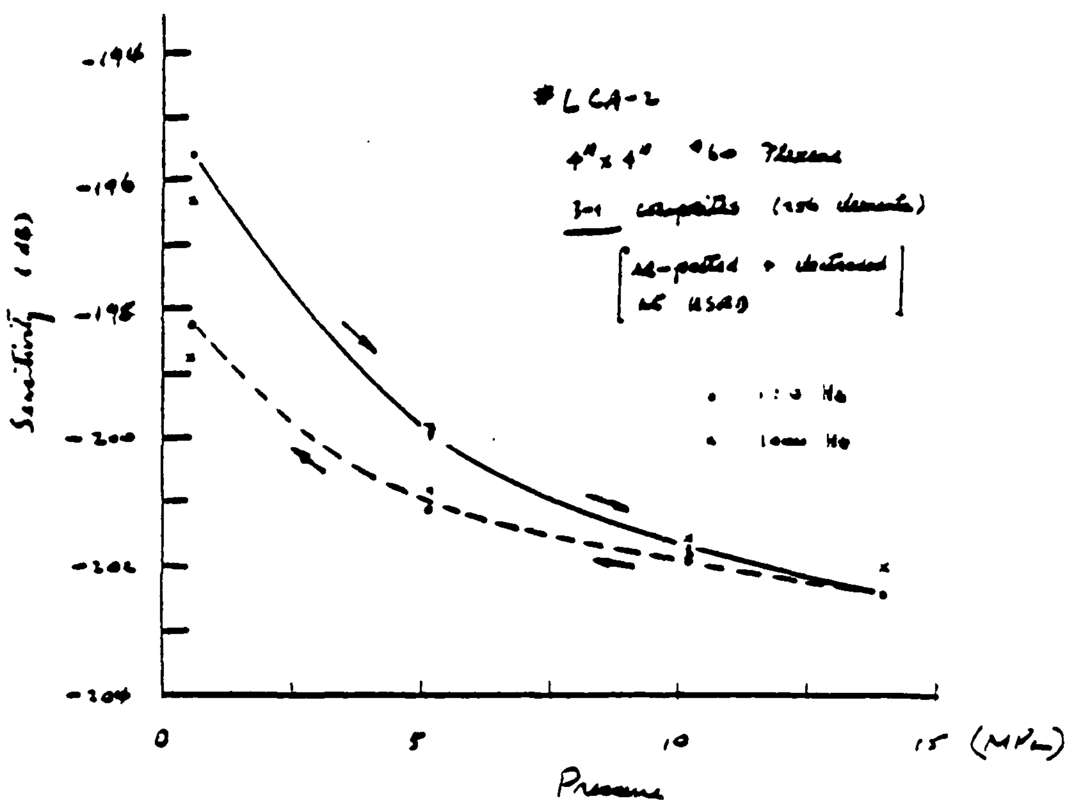
Dielectric Loss: .0151

Mean d_{33}: 225-380

Mean element capacitance: 32.0 pF

Mean element loss: 0.0250


#LCA-2
4" x 4"
3-1
dB
-193
-195
-197
-199
-201
-203
1
2
3
4
5
6
7
8
9
10
Frequency (x10² Hz)
750
1450
2000


#LCA-2
-194
-196
-198
-200
-202
-204
0
5
10
15 (MPa)
Pressure

USRD - Orlando

Test Data

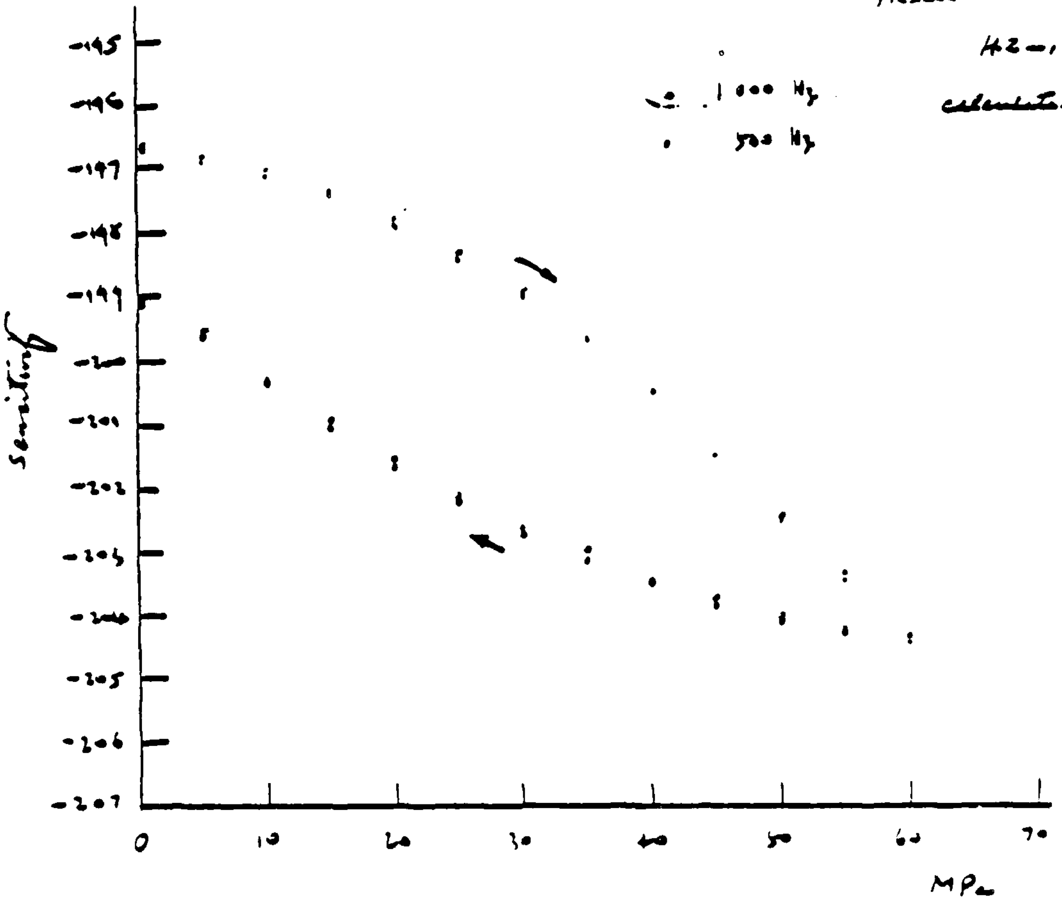
on

1''x1'' Conformal Array

Old MRL No. H2-17a-1
New MRL No. FLEX 41
Orlando No. H2-17a-1

MRL Description: See Appendix A

1-3 composite, 1st sample
Flexane #60
HZ-17a-1
calculated sensitivity



USRD - Orlando

Test Data

on

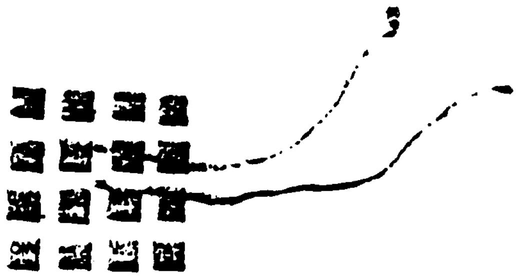
1''x1'' Conformal Array

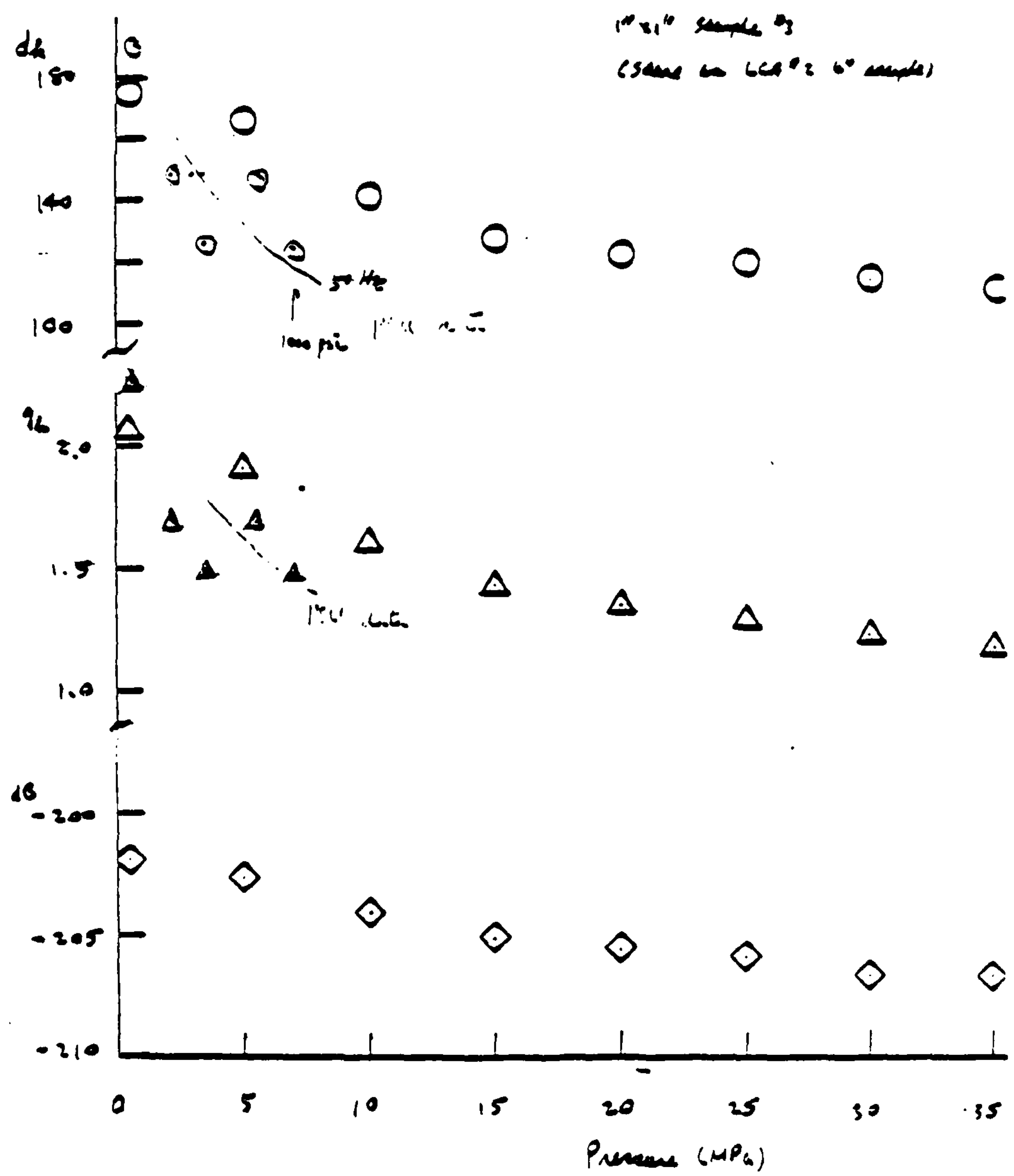
Old MRL No.

New MRL No. FLEX 37

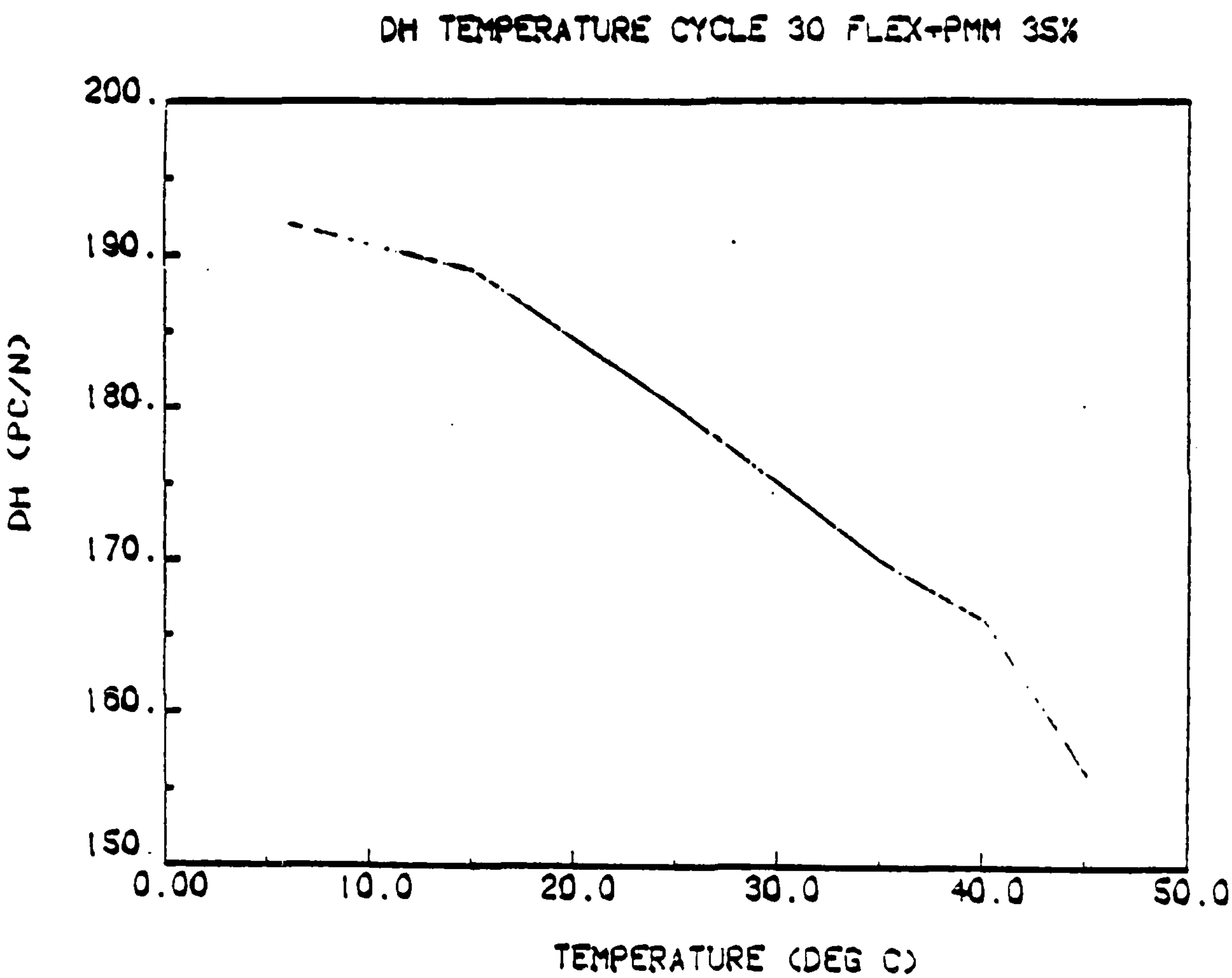
Orlando No. 3 or FLEX 3

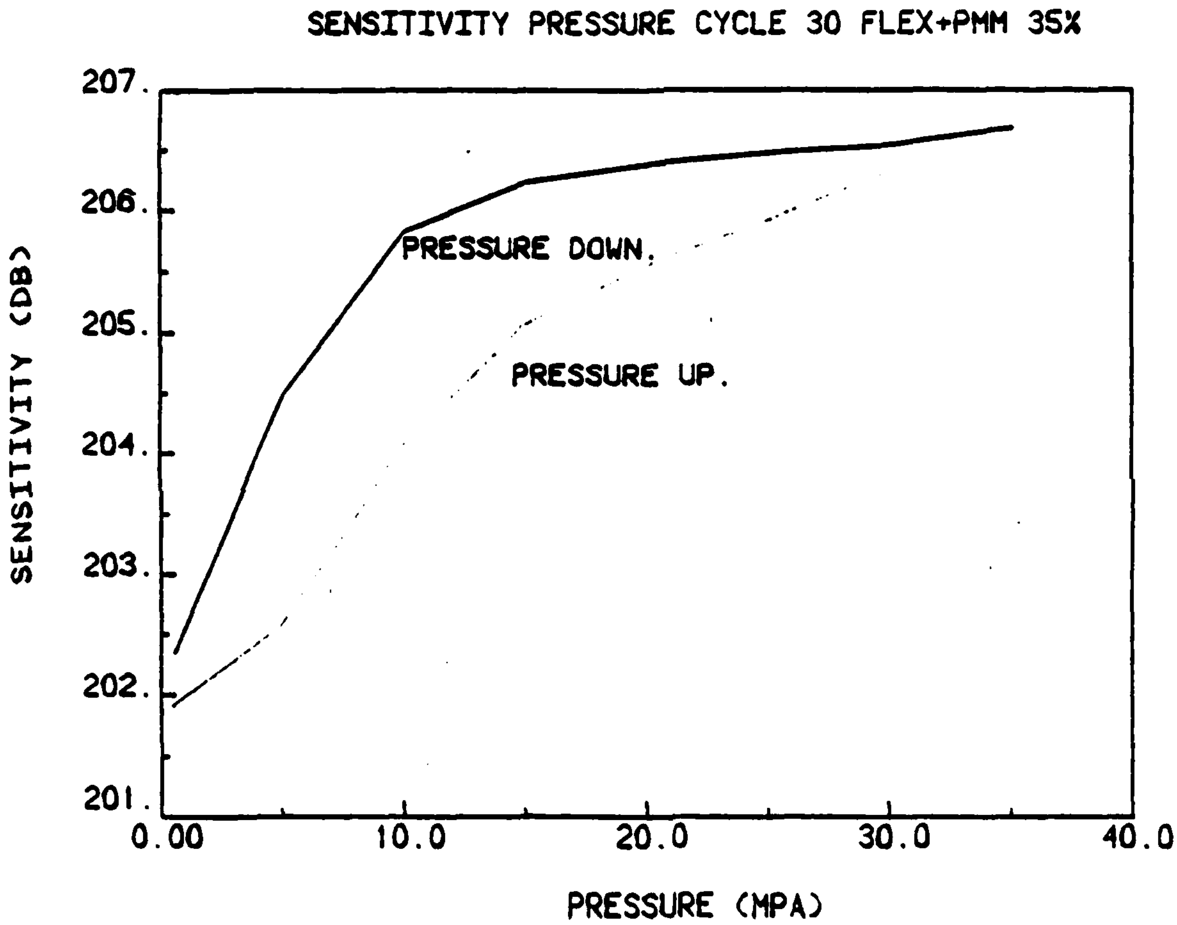
MRL Description: See Appendix A



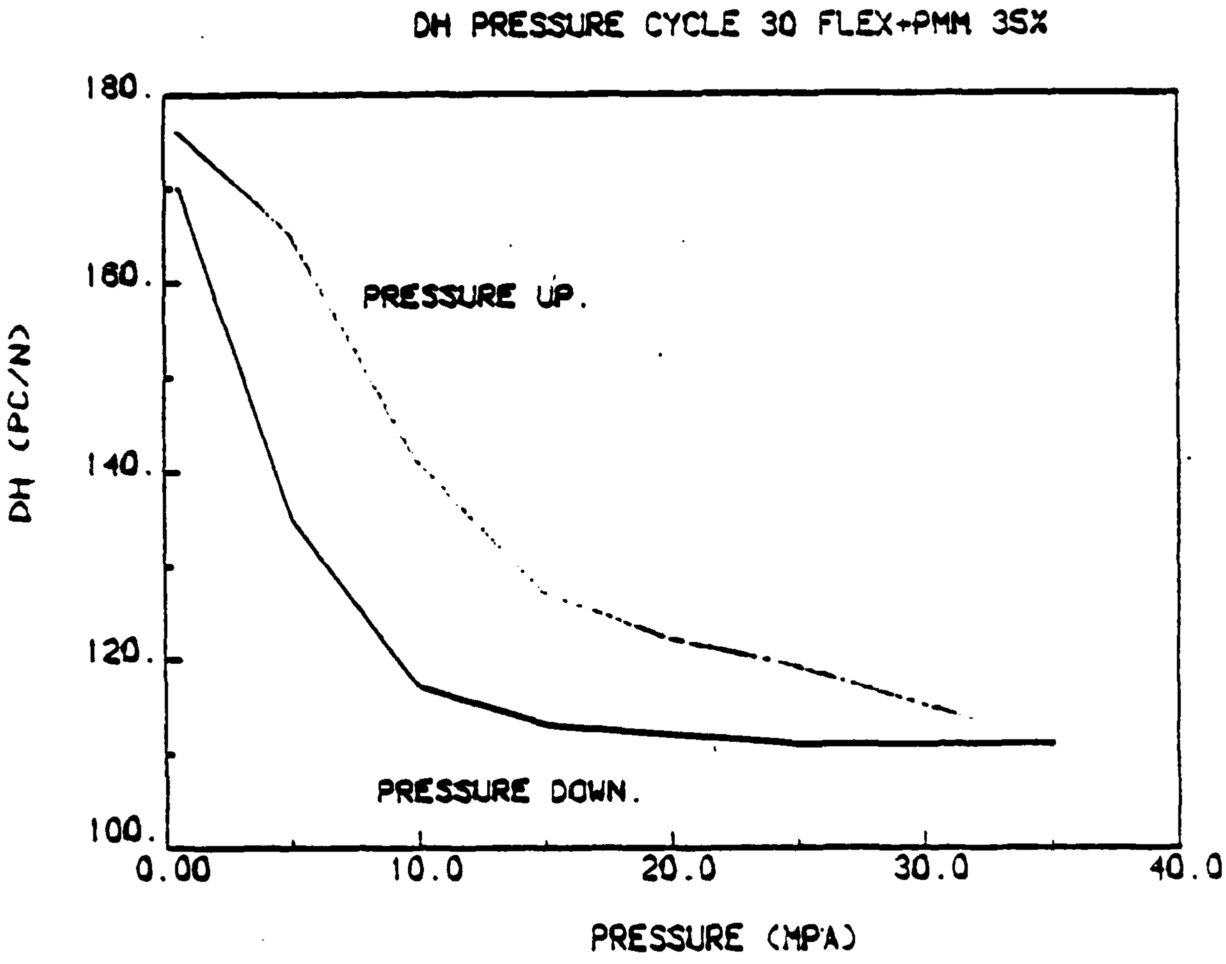


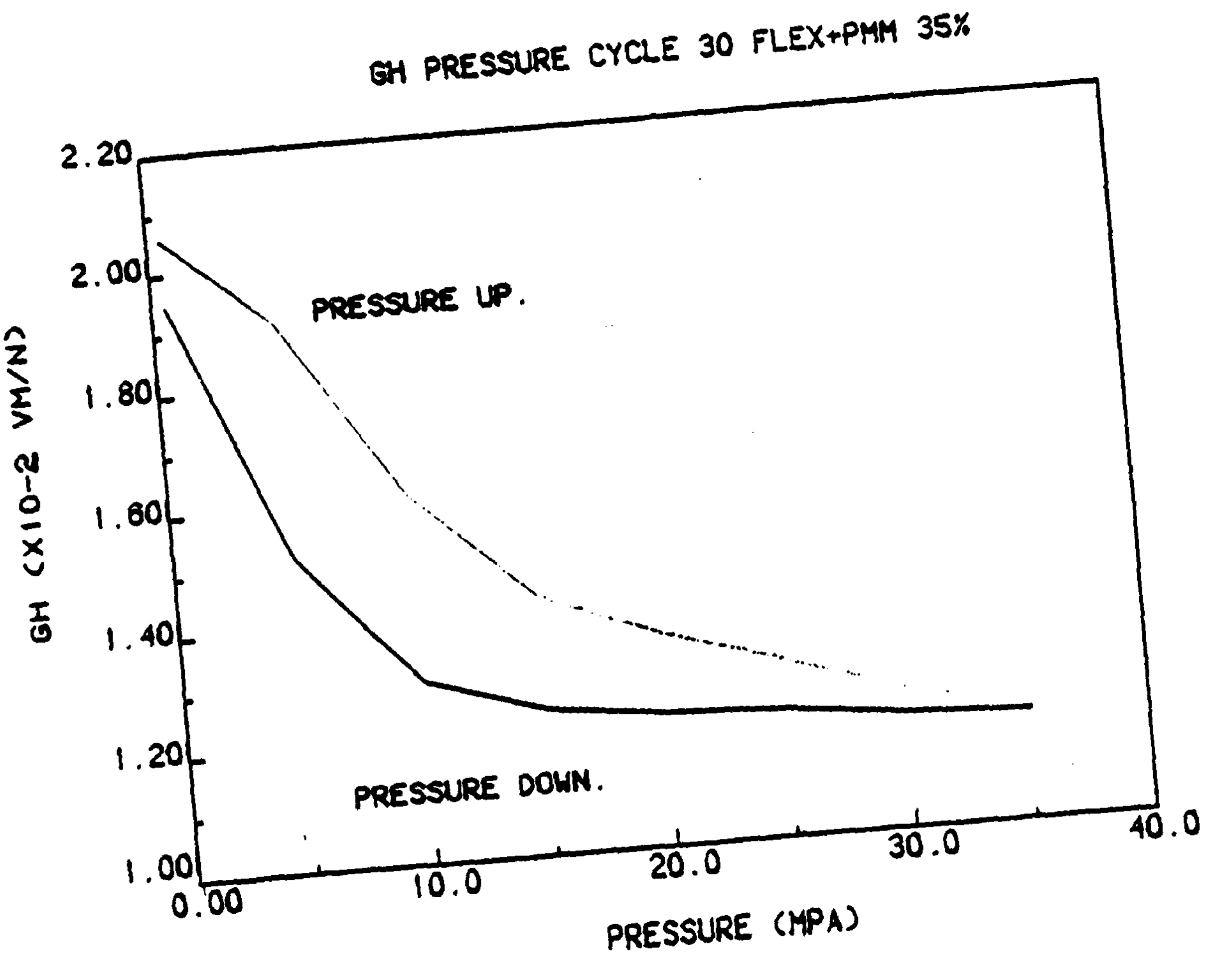
1"x1" Sample #3
(Same as LCA #2 6" sample)
dB
180
140
100
50 Hz
1000 psi
%
2.0
1.5
1.0
dB
-200
-205
-210
0
5
10
15
20
25
30
35
Pressure (MPa)

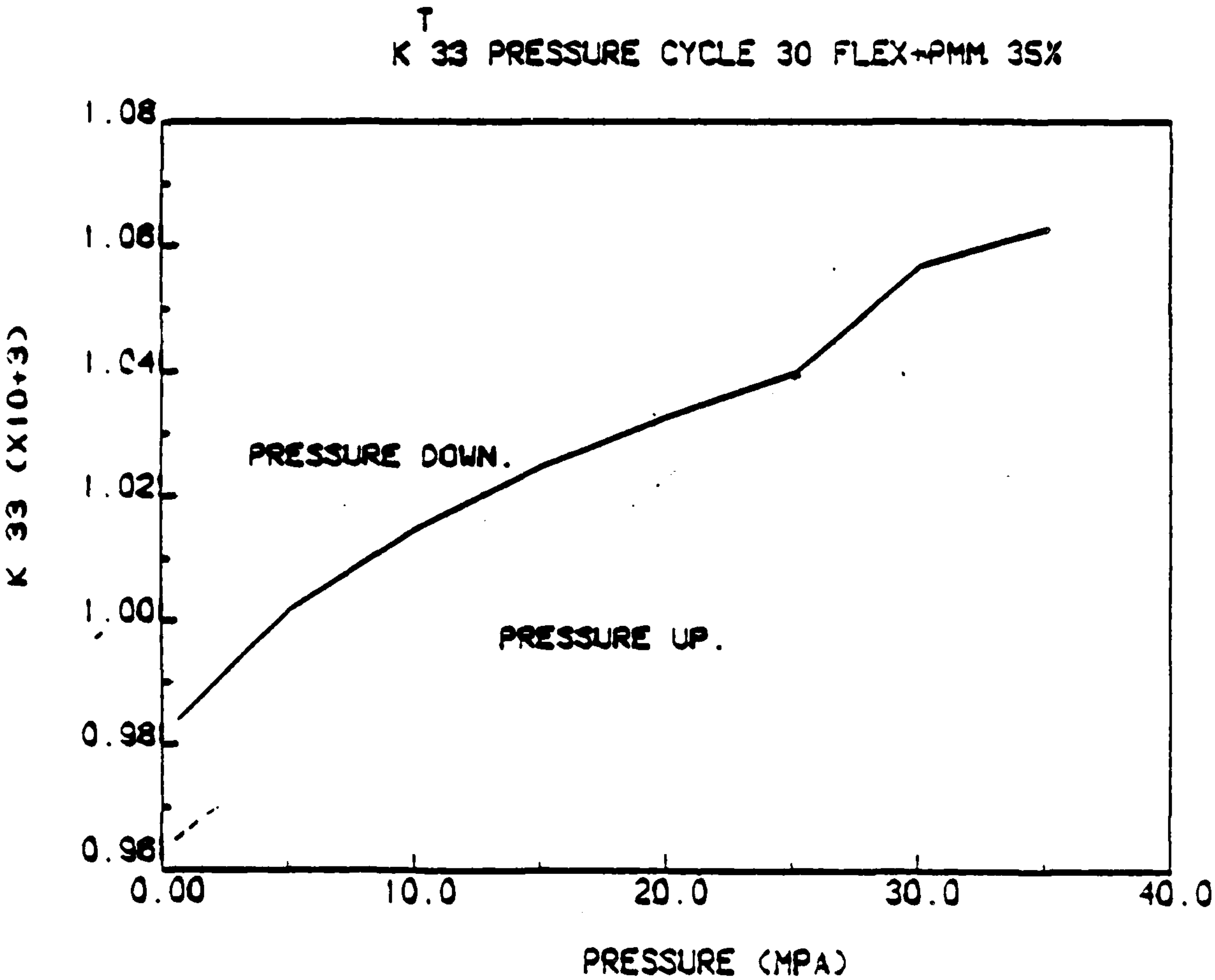

DH TEMPERATURE CYCLE 30 FLEX-PMM 35%
200.
190.
180.
170.
160.
150.
DH (PC/N)
0.00
10.0
20.0
30.0
40.0
50.0
TEMPERATURE (DEG C)



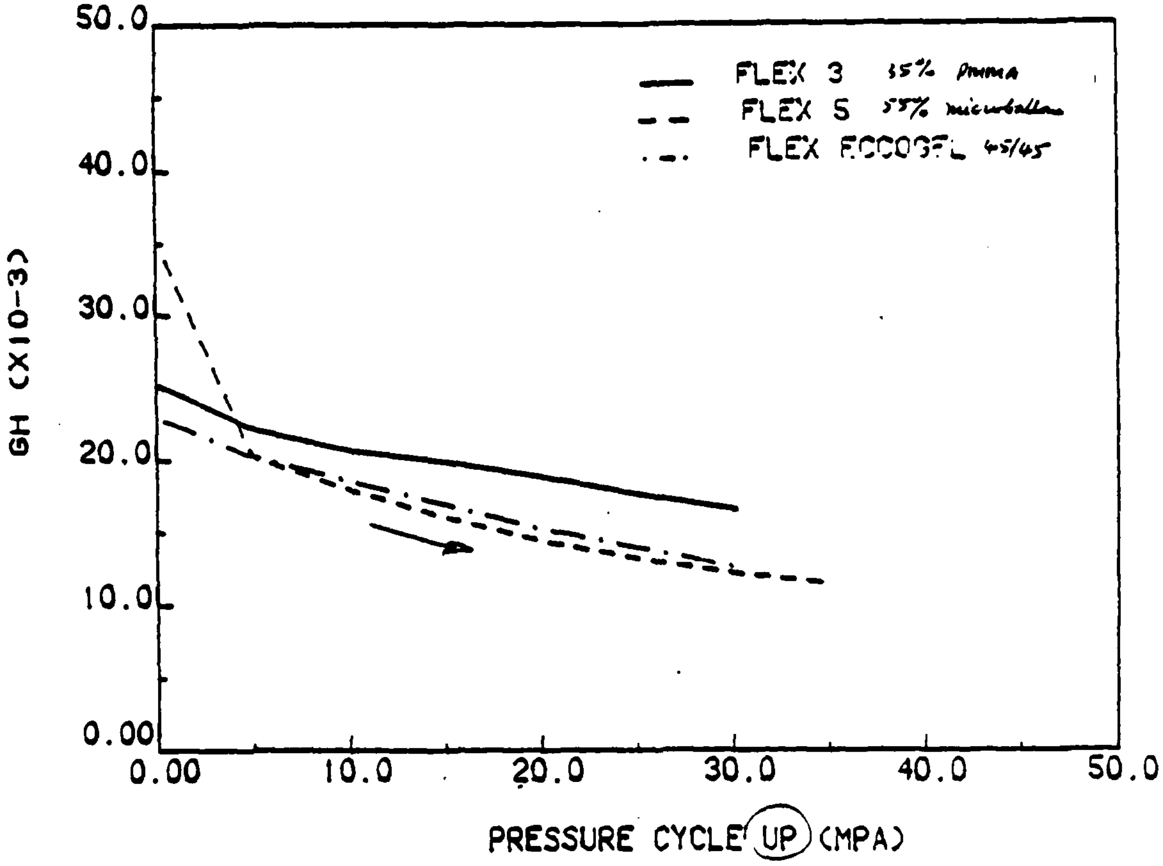
SENSITIVITY PRESSURE CYCLE 30 FLEX+PMM 35%
207.
206.
205.
204.
203.
202.
201.
SENSITIVITY (DB)
PRESSURE DOWN.
PRESSURE UP.
0.00
10.0
20.0
30.0
40.0
PRESSURE (MPA)


DH PRESSURE CYCLE 30 FLEX+PMM 35%
180.
160.
140.
120.
100.
DH (PC/N)
PRESSURE UP.
PRESSURE DOWN.
0.00
10.0
20.0
30.0
40.0
PRESSURE (MPA)

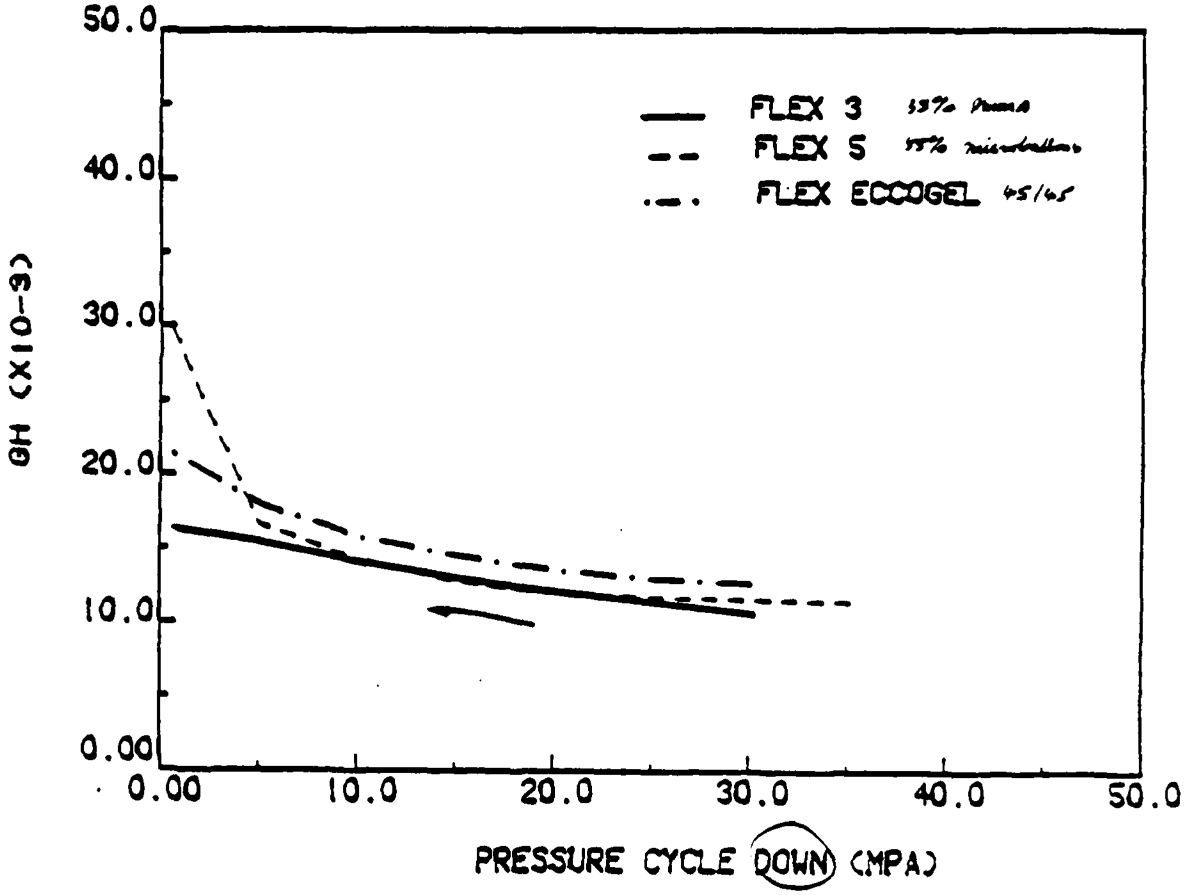

GH PRESSURE CYCLE 30 FLEX+PMM 35%
2.20
2.00
1.80
1.60
1.40
1.20
1.00
GH (X10-2 VM/N)
PRESSURE UP.
PRESSURE DOWN.
0.00
10.0
20.0
30.0
40.0
PRESSURE (MPA)


T
K 33 PRESSURE CYCLE 30 FLEX+PMM 35%
1.08
1.06
1.04
1.02
1.00
0.98
0.96
K 33 (X10+3)
PRESSURE DOWN.
PRESSURE UP.
0.00
10.0
20.0
30.0
40.0
PRESSURE (MPA)

FLEX ECCOGEL, 3, 5



FLEX ECCOGEL, 3, 5



USRD - Orlando

Test Data

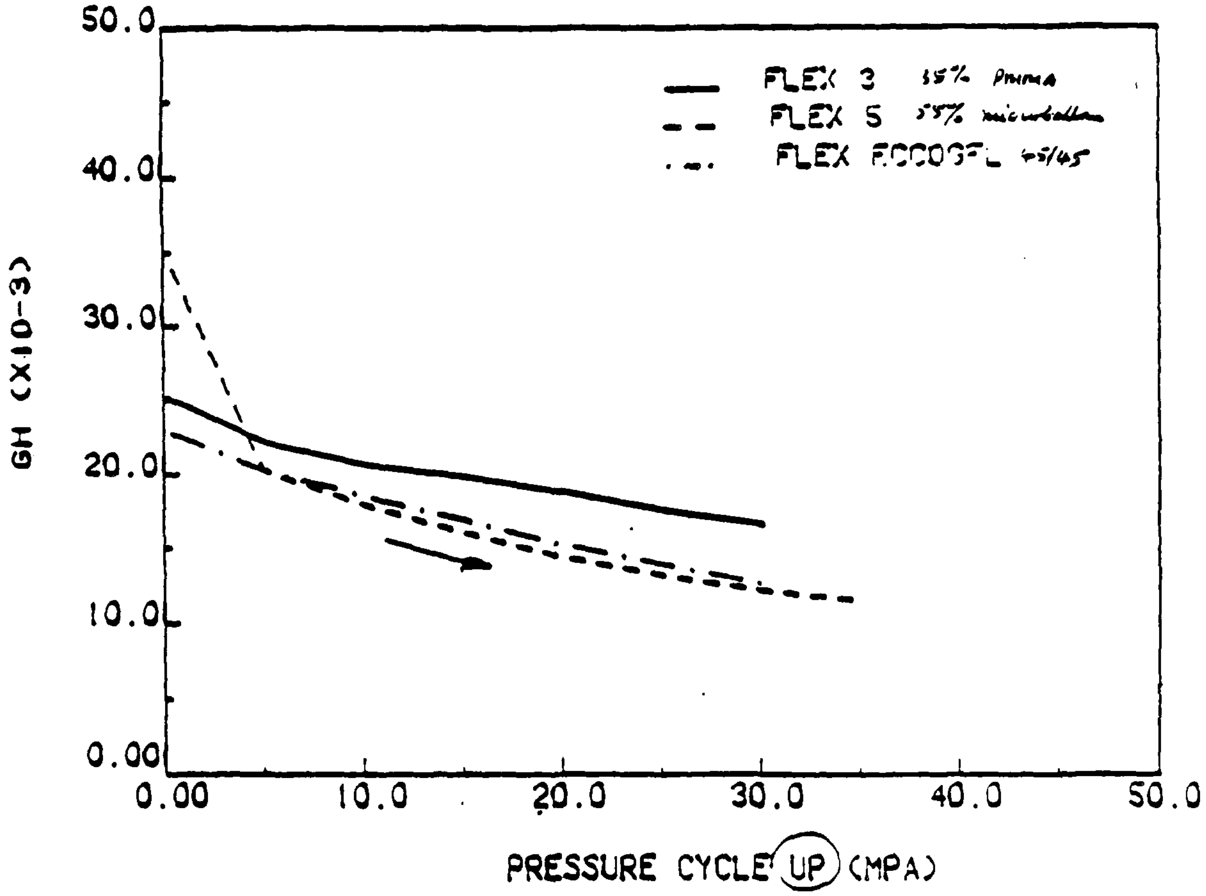
on

1''x1'' Conformal Array

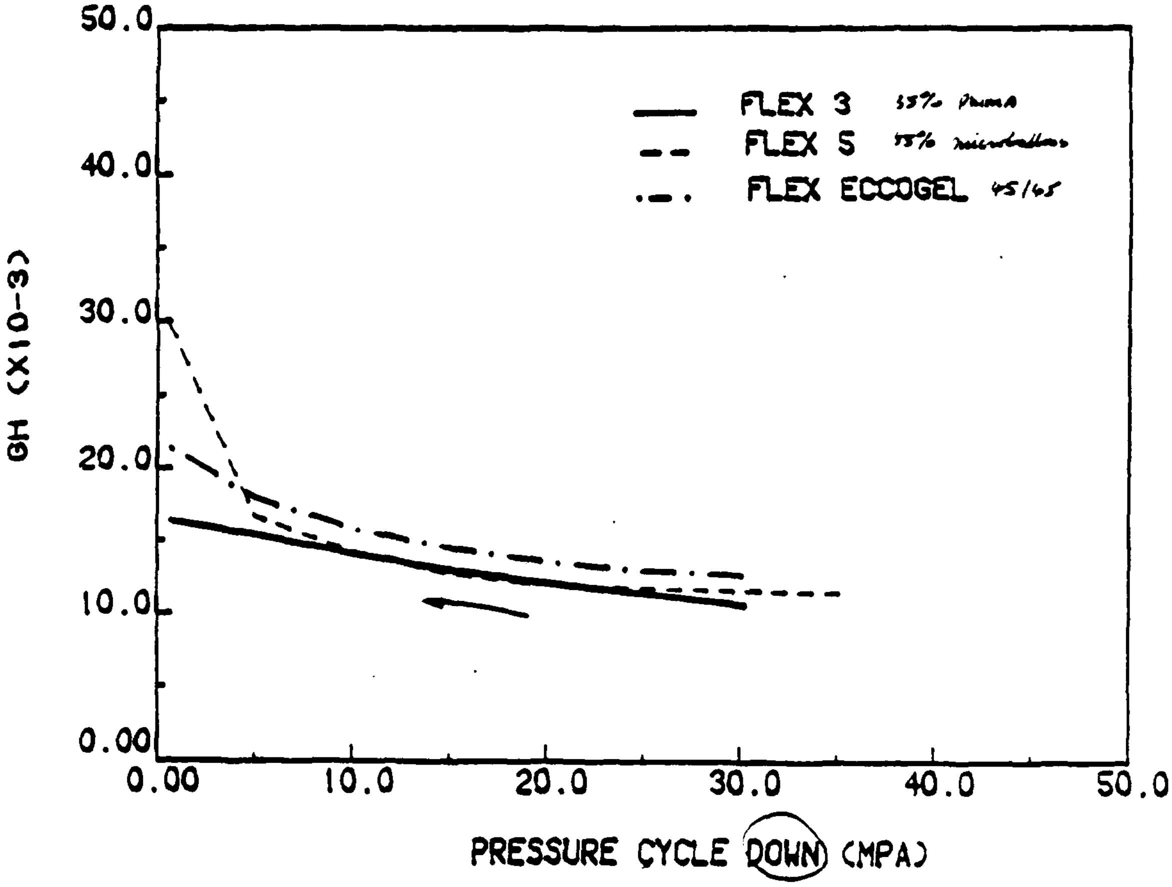
Old MRL No.
New MRL No. FLEX 39
Orlando No. 5 or FLEX 5

MRL Description: See Appendix A

FLEX ECCOGEL, 3, 5



FLEX ECCOGEL, 3, 5



USRD - Orlando

Test Data

on

1''x1'' Conformal Array

Old MRL No.
New MRL No. ECCO 09
Orlando No. ECCOGEL 45/45, FLEX ECCOGEL 45/45

MRL Description: See Appendix A

NAVAL RESEARCH LABORATORY
UNDERWATER SOUND REFERENCE DETACHMENT
P. O. BOX 8337
ORLANDO, FLORIDA 32856

$T = 24.5°C$

PRESSURE CYCLE 0.50 TO 30.00 FOR ECCOGEL 1365-45 4X4 45/45

PRESS	(DH)	(GH)	(K33)	(SEN)	(CAP)	(DISS)
MPA	PC/N	VM/N (X10-3)		DB.	PF.	(X10-2)
0.50	189.00	22.80	937.00	-200.95	530.70	1.84
5.00	195.00	20.40	959.00	-201.96	543.40	1.83
10.00	195.00	18.70	1000.00	-202.71	566.70	1.87
15.00	195.00	17.00	1004.00	-203.55	569.20	1.83
20.00	196.00	15.30	1025.00	-204.85	580.80	1.82
25.00	196.00	14.00	1039.00	-203.77	588.50	1.82
30.00	196.00	12.70	1048.00	-206.06	593.70	1.83
	d_h	g_h	K_{33}^T	Sensitivity re 1 V/μPa	capacitance	dielectric dissipation

NAVAL RESEARCH LABORATORY
UNDERWATER SOUND REFERENCE DETACHMENT
P. O. BOX 8337
ORLANDO, FLORIDA 32856

T = 24.5°C

PRESSURE CYCLE 30.00 TO 0.50 FOR ECCOGEL 1365-45 4X4 45/45

PRESS	(DH)	(GH)	(K33)	(SEN)	(CAP)	(DISS)
MPA	PC/N	VM/N (X10-3)		DB.	PF.	(X10-2)
30.00	196.00	12.70	1048.00	-206.06	593.70	1.83
25.00	196.00	13.00	1042.00	-205.82	590.40	1.81
20.00	196.00	13.60	1036.00	-205.43	587.10	1.82
15.00	195.00	14.50	1028.00	-204.89	582.30	1.83
10.00	195.00	15.80	1019.00	-204.16	577.20	1.86
5.00	195.00	18.00	1001.00	-203.07	567.30	1.88
0.50	194.00	21.50	979.00	-201.50	554.50	1.93

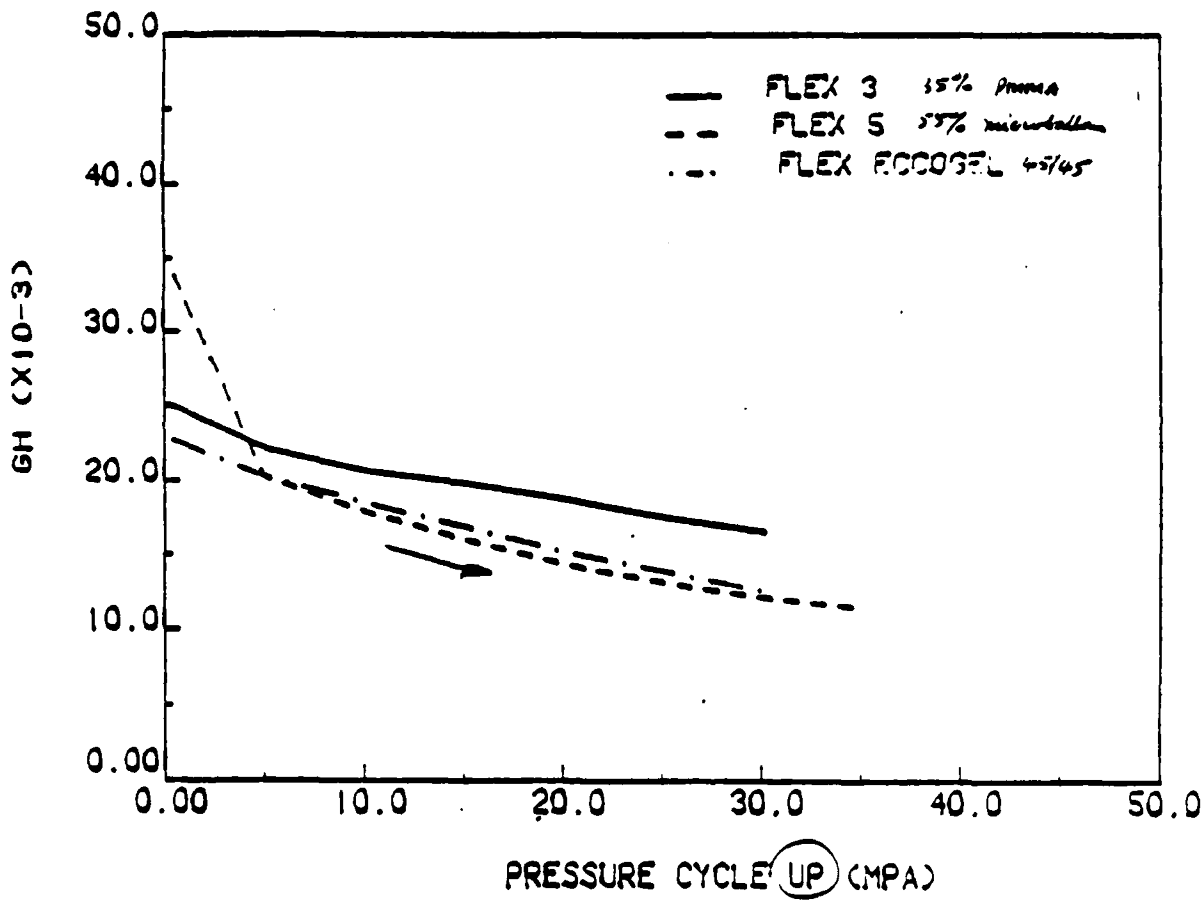
NAVAL RESEARCH LABORATORY
UNDERWATER SOUND REFERENCE DETACHMENT
P. O. BOX 8337
ORLANDO, FLORIDA 32856

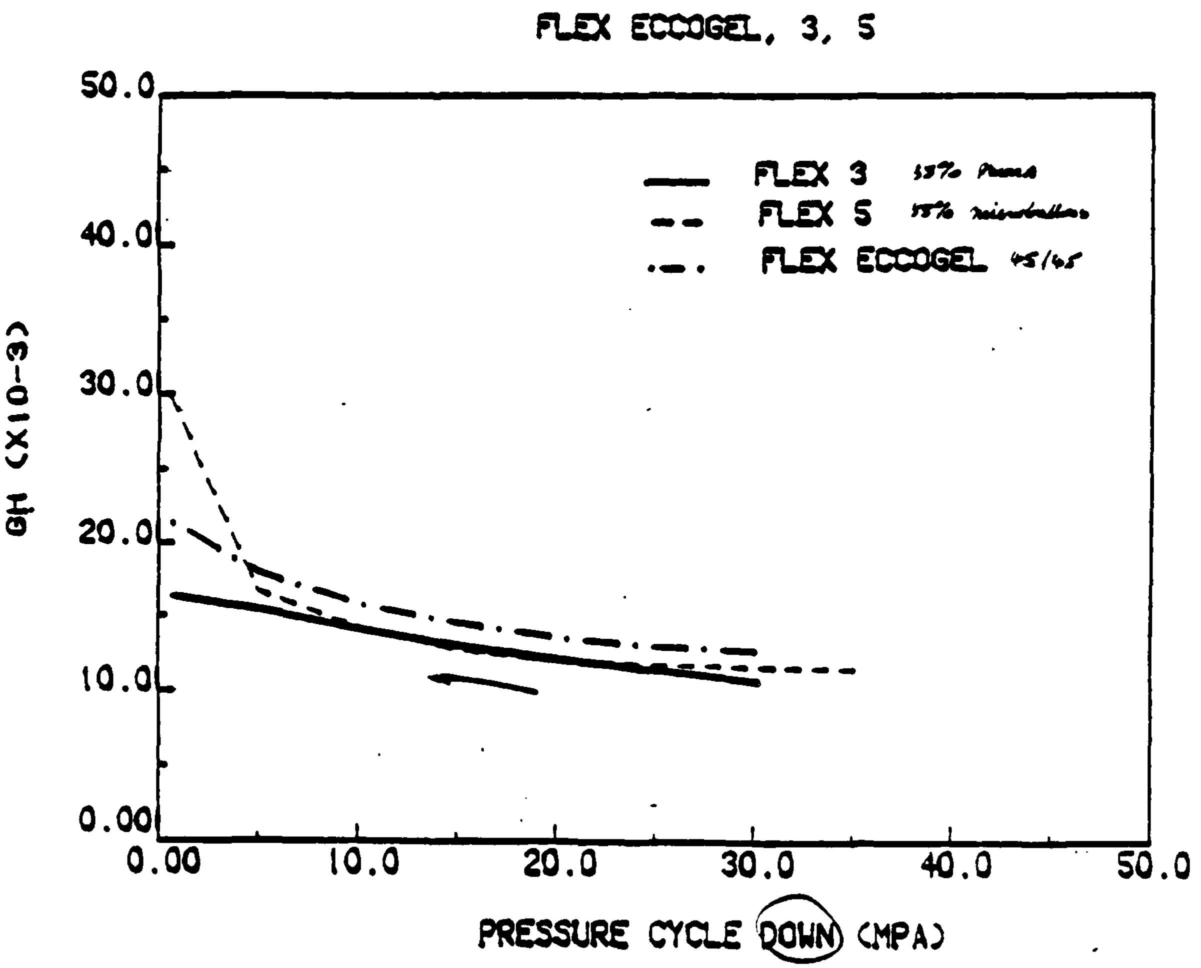
p = 0.5 MPa

TEMPERATURE CYCLE 5.10 TO 34.90 FOR ECCOGEL 1365-45 4X4 45/45

TEMP	(DH)	(GH)	(K33)	(SEN)	(CAP)	(DISS)
DEG C	PC/N	VM/N (X10-3)		DB.	PF.	(X10-2)
5.10	192.00	30.30	912.00	-200.62	516.70	2.17
10.20	192.00	30.10	923.00	-200.72	523.00	2.10
15.00	190.00	29.80	930.00	-200.86	526.80	2.02
20.20	187.00	29.50	938.00	-201.07	531.30	1.97
25.10	184.00	29.20	943.00	-201.25	534.50	1.93
30.20	181.00	28.90	953.00	-201.50	539.90	1.99
34.90	177.00	28.50	961.00	-201.75	544.60	2.06

FLEX ECCOGEL, 3, 5




FLEX ECCOGEL, 3, 5
FLEX 3
FLEX 5
FLEX ECCOGEL 45/45
GH (X10-3)
50.0
40.0
30.0
20.0
10.0
0.00
0.00
10.0
20.0
30.0
40.0
50.0
PRESSURE CYCLE DOWN (MPA)

6.0 Conclusions

1) The conformal arrays developed in this work appear to be limited by the basic characteristics of the transducers from which they are fabricated. Many aspects of array construction have been investigated some of which enhance the properties of the array including:

a) Stiff-electrode stress enhancement

b) Matrix fillers for enhancement of low pressure sensitivity

c) Closer element spacing to enhance area dependent properties such as d_h and permittivity

d) Effect of matrix vs jacket hardness in arrays where the elements are especially effected by transverse stress (i.e., 3-1 perforated blocks).

2) Two elastomer systems have been investigated (polyurethane and epoxy) and the advantage of each has been determined: the epoxy has better polymer/ceramic bonding, better self bonding, it has a longer pot life and its lower viscosity makes it easier to achieve void-free embeddments. It is slightly prone to fracture and it is difficult (at least with the system used here) to use with fillers. The polyurethane is more amenable to fillers and foaming to enhance low pressure properties.

3) It is obvious from the data that some of the aspects of this investigation have been obscured by the lack of large quantities of transducer elements with uniform properties. It should be obvious that this is impossible to achieve with the resources available at MRL although much of the development work that will be required for a scale up in a production setting has been initiated here.

4) It is not possible with the present facilities at the Materials Research Lab to produce production quantities of the transducer elements required for large scale-up devices. As can be seen in the procedures

section, production scale up did not work primarily because of equipment limitations (i.e., extruded 3-1 elements). This is not to say that large scale-up is not feasible but rather that it is not feasible at MRL, at least under current equipment restrictions. The procedures used for the present work are manpower intensive. Due to technical staff limitations, large number of uniform parts (i.e., individual elements) are unlikely to be forthcoming. As element production work proceeds at industrial sites (such as Celanese Corp.) MRL interaction in preparing larger devices may be more effective.

7.0 Future Work

Because of manpower restrictions, it has been decided that any future work should be done on conformal arrays of much smaller size (maximum: 2''x2'' 100 element arrays).

Because of the conclusion that the arrays investigated to date are limited by element characteristics a modified element will be investigated. This will consist of the 3-1 perforated block, ultrasonically machined, but with a larger perforation and smaller wall thickness. The perforation will be empty with alumina cover plates epoxied in place. Matrix material will not intrude into the center portion of the perforated block, but the alumina plates will reinforce the block and so devalue the g_h response somewhat.

Several samples prepared in this way show improved g_h values but with lower permittivity. A series of array sizes including 1/2"-4 elements, 1"-25 elements and 2"-100 elements will be prepared to evaluate the effect of array size on scale-up properties.

APPENDIX A

Hydrostatic Voltage Coefficient Versus Pressure Graphs

and Detailed Data for 1''x1'' Arrays

Cycle 01

C= 547.53pF KE= 966.25 KC= 384.1 d33= 265pC/N ELMA= 3.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
50	21.15	-201.45	180.94	3826.92	71.93	[illegible]
100	23.90	-200.39	204.47	4886.80	81.28	1942.58
300	24.26	-200.26	207.55	5035.13	82.50	2001.55
500	23.56	-200.52	201.56	4748.75	80.12	1887.71
700	23.90	-200.39	204.47	4886.80	81.28	1942.58
1000	22.99	-200.73	176.68	4521.75	78.18	1777.47

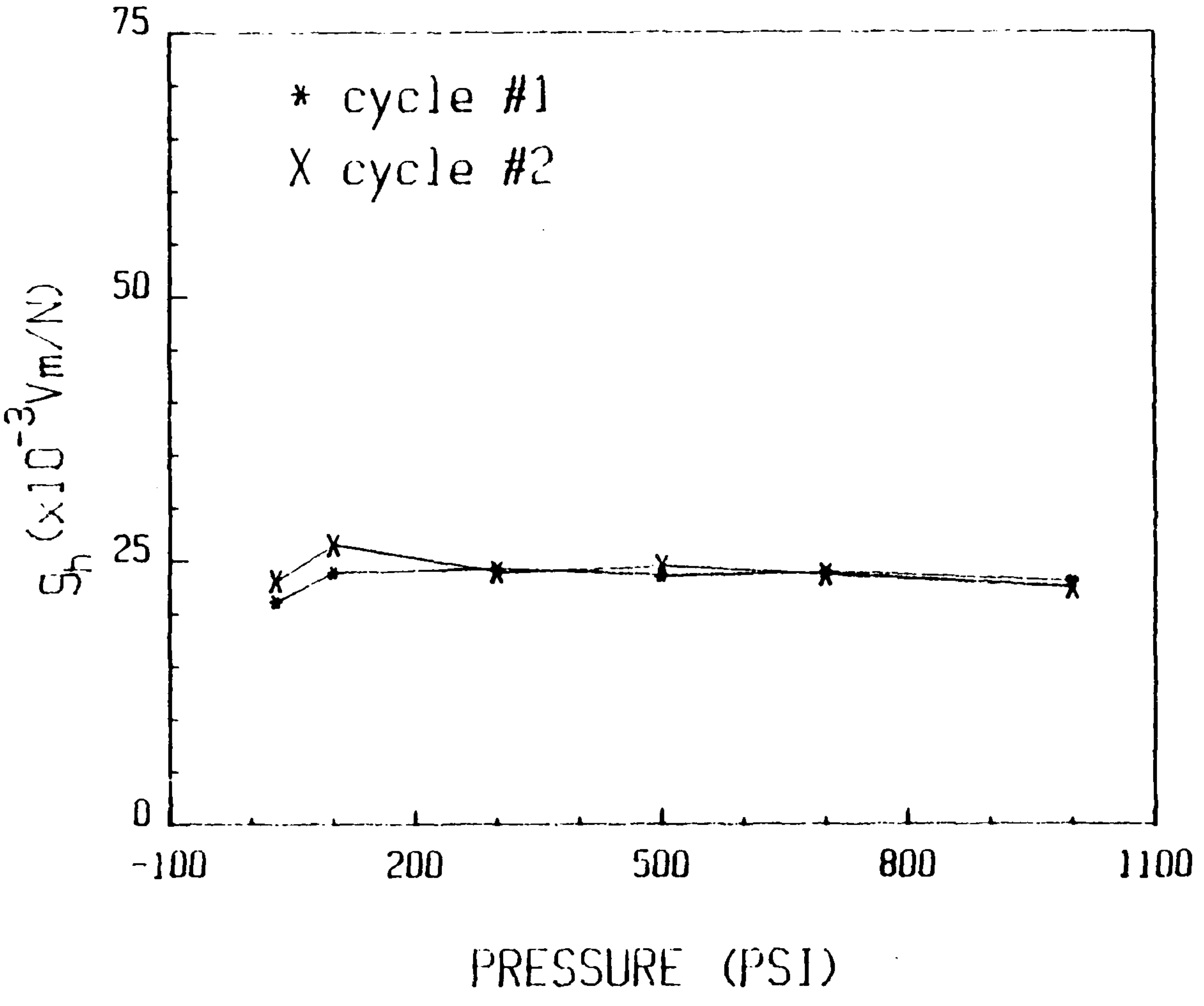
Cycle 02

C= 547.53pF KE= 966.25 KC= 384.1 d33= 265pC/N ELMA= 3.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
50	23.16	-200.66	195.14	4508.87	[illegible]	[illegible]
100	26.52	-199.49	226.88	6016.95	90.19	[illegible]
300	23.95	-200.37	204.90	4907.27	81.45	[illegible]
500	24.48	-200.18	209.43	5126.06	83.25	[illegible]
700	23.67	-200.47	202.50	4793.20	80.50	[illegible]
1000	22.44	-200.94	191.98	4307.99	[illegible]	[illegible]

Eccogel 1365-0 Matrix and 1365-0 Jacket.
16,3-1 Machined Safari PZT elements.
Center hole filled with Tra-bond 3112 Epoxy.
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.

ECCO 01



* cycle #1
X cycle #2
g_h ($\times 10^{-3}$ Vm/N)
75
50
25
0
-100
200
500
800
1100
PRESSURE (PSI)

Cycle 01

C= 532.9pf KE= 940.43 KC= 373.84 d33= 265pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	25.18	-199.94	209.66	5279.31	83.35	2098.63
100	27.36	-199.22	227.81	6233.02	90.56	2477.75
300	25.34	-199.88	211.00	5346.62	83.87	2125.39
500	24.85	-200.05	206.92	5141.84	82.25	2043.99
700	24.71	-200.10	205.75	5084.07	81.79	2021.02
1000	22.93	-200.75	190.93	4377.78	75.90	1740.34

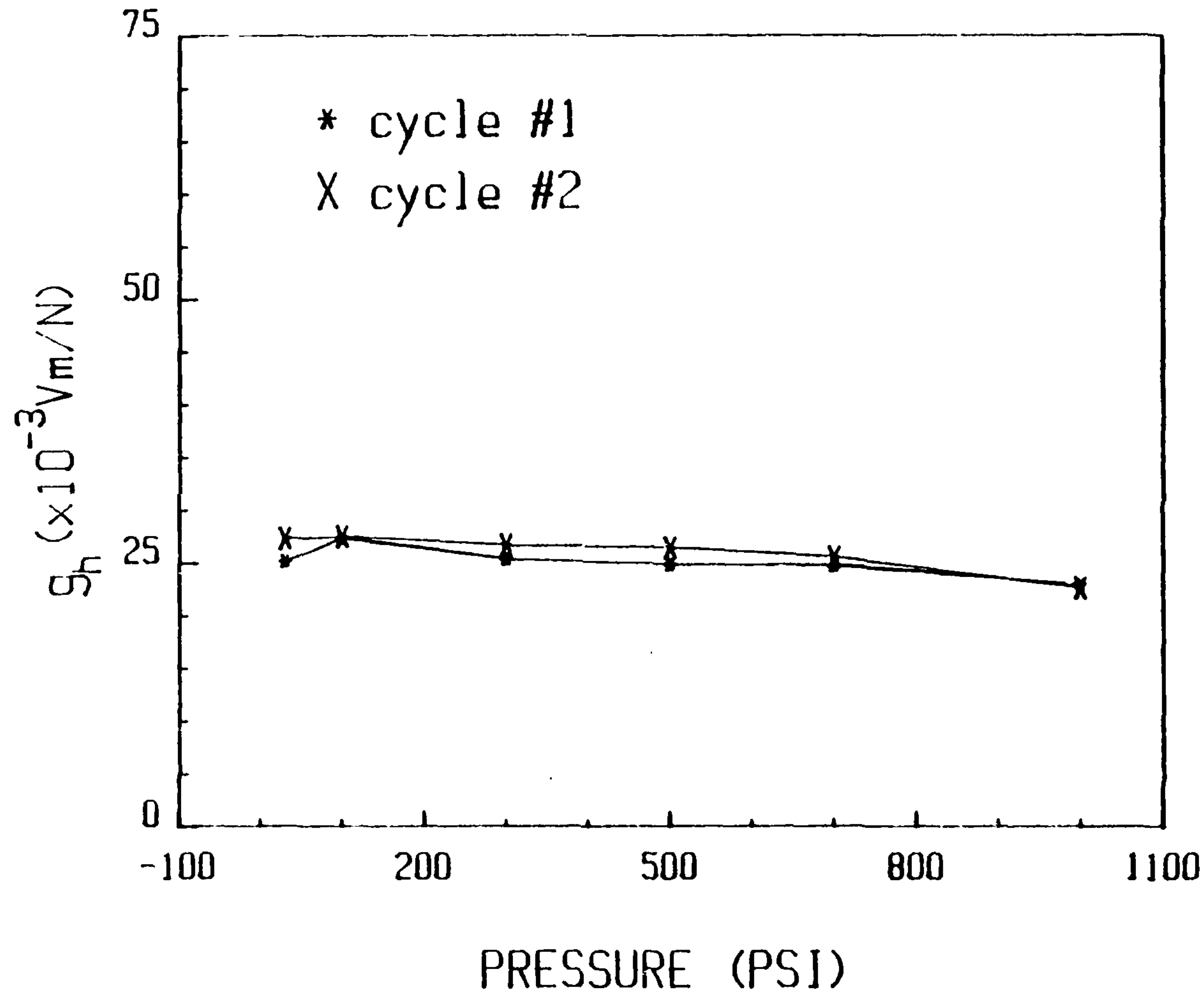
Cycle 02

C= 532.9pf KE= 940.43 KC= 373.84 d33= 265pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	27.32	-199.23	227.48	6214.80	90.43	2470.51
100	27.51	-199.17	229.06	6301.55	91.06	2504.99
300	26.66	-199.44	221.99	5918.15	88.24	2352.59
500	26.43	-199.52	220.07	5816.48	87.48	2312.17
700	25.52	-199.82	212.49	5422.35	84.47	2155.07
1000	22.58	-200.88	188.01	4245.35	74.74	1687.61

Eccogel 1365-25 Matrix and 1365-0 Jacket.
16,3-1 Machined Safari PZT elements.
Center hole filled with Tra-bond 2113 Epoxy.
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.

ECCO 02



75
50
25
0
* cycle #1
X cycle #2
g_h (x10^{-3}Vm/N)
-100
200
500
800
1100
PRESSURE (PSI)

Cycle 01

C= 505.78pf KE= 892.57 KC= 354.81 d33= 313pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	25.24	-199.92	199.47	5034.55	79.29	2001.31
100	22.20	-201.03	175.44	3894.82	69.74	1548.25
300	19.95	-201.96	157.66	3145.34	62.67	1250.32
500	16.11	-203.82	127.31	2051.03	50.61	815.32
700	14.73	-204.59	116.41	1714.70	46.27	681.62
1000	18.99	-202.39	150.07	2849.91	59.66	1132.88

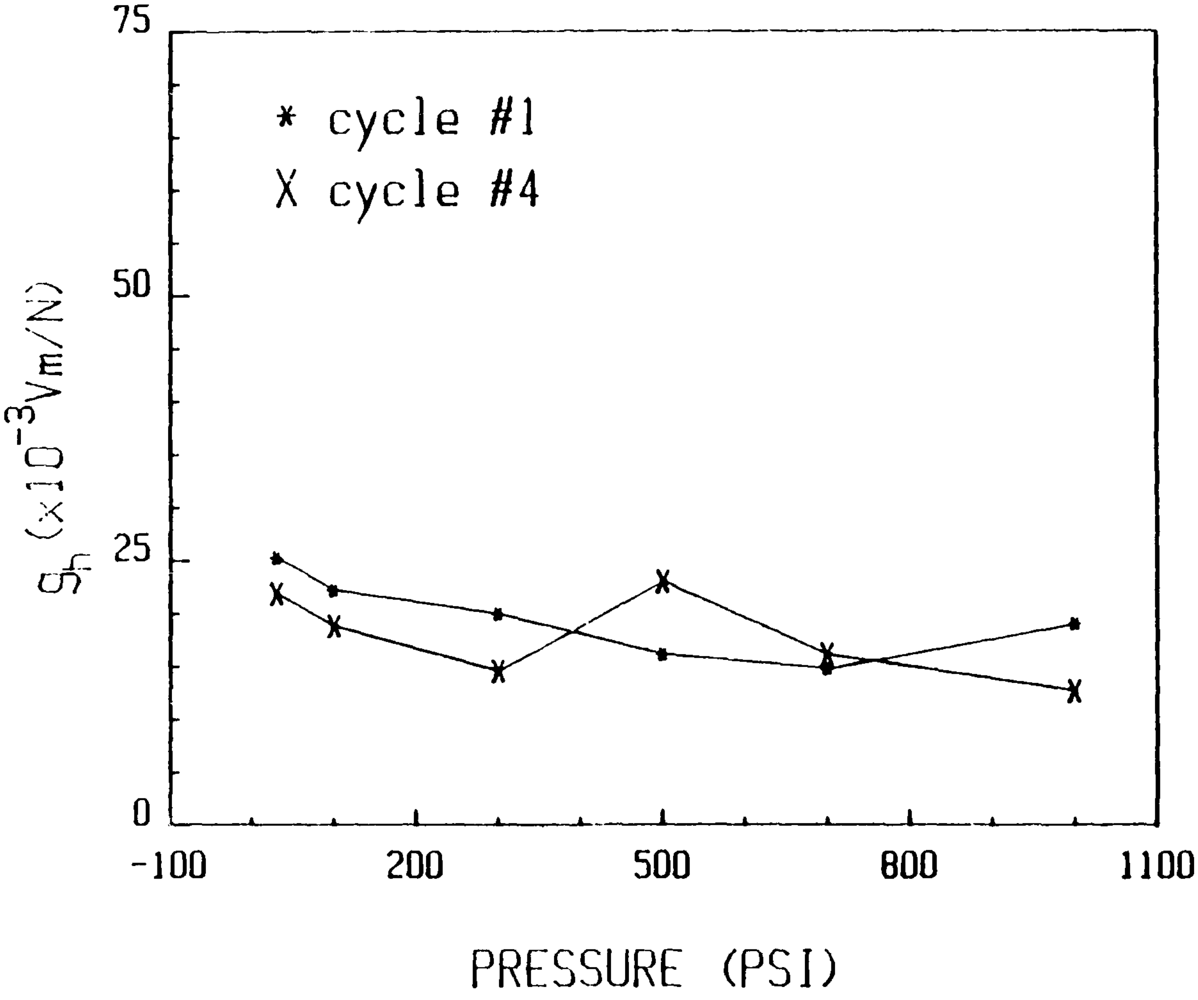
Cycle 04

C= 505.78pf KE= 892.57 KC= 354.81 d33= 313pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	21.91	-201.15	173.15	3793.73	68.83	1508.07
100	18.81	-202.47	148.65	2776.14	59.09	1111.51
300	14.58	-204.68	115.22	1679.95	45.80	667.81
500	23.01	-200.72	181.84	4184.23	72.29	1663.29
700	16.11	-203.82	127.31	2051.03	50.61	815.32
1000	12.66	-205.91	100.05	1266.63	39.77	503.50

Eccogel 1365-0 Matrix and 1365-25 Jacket.
16, 3-1 Machined Safari PZT elements.
Center hole filled with Tra-Bond 2113 Epoxy.
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.

ECCO 03



* cycle #1
X cycle #4
75
50
25
0
g_h ($\times 10^{-3}$ Vm/N)
-100
200
500
800
1100
PRESSURE (PSI)

Cycle 05

C= 486.29pf KE= 858.17 KC= 341.14 d33= 365pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

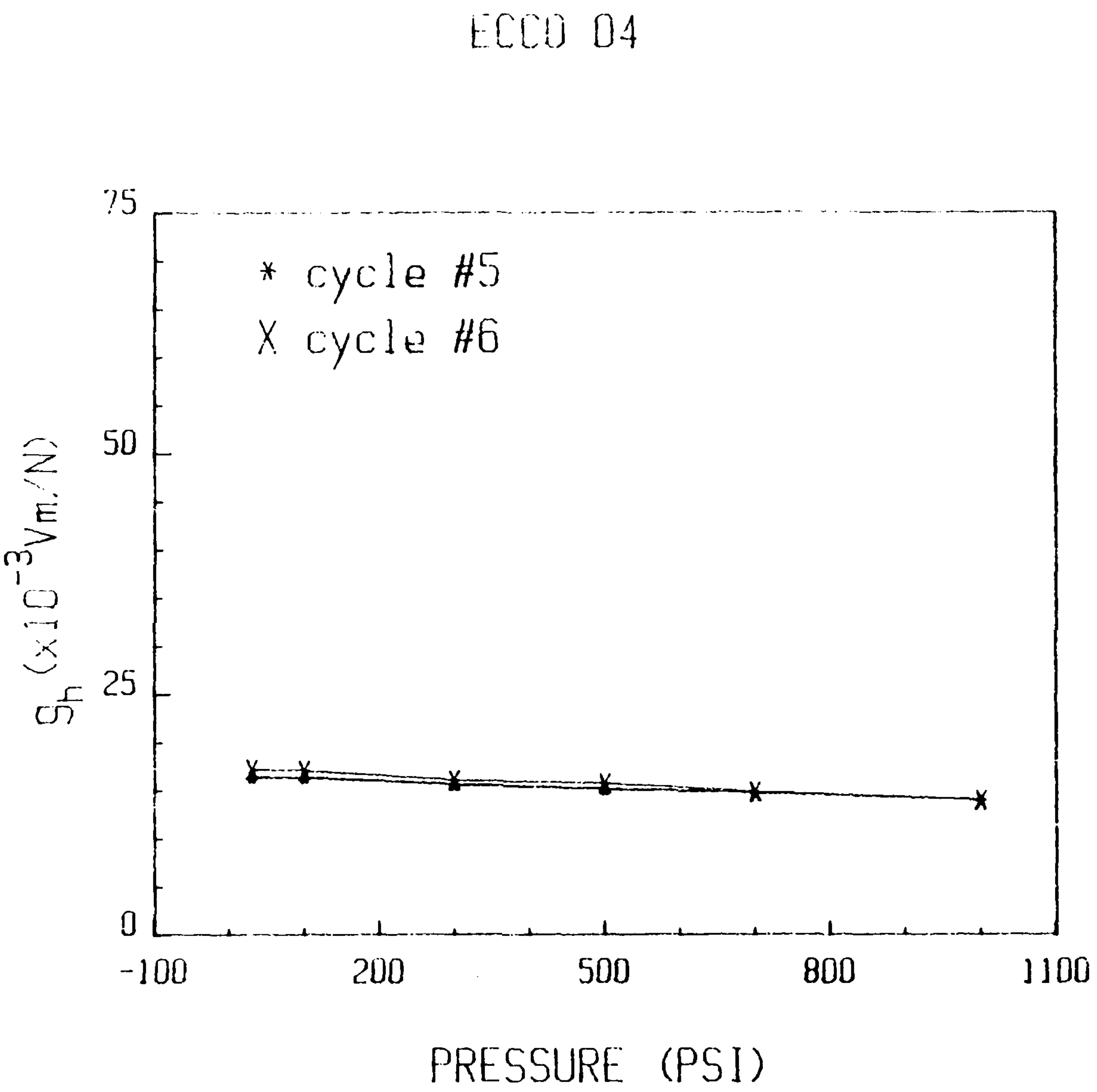
			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	16.37	-203.68	124.38	2036.15	49.44	809.41
100	16.30	-203.72	123.85	2018.78	49.23	802.50
300	15.57	-204.11	118.30	1842.00	47.03	732.23
500	15.08	-204.39	114.58	1727.39	45.55	686.87
700	14.71	-204.61	111.77	1644.14	44.43	653.58
1000	13.95	-205.07	106.00	1478.64	42.14	587.79

Cycle 06

C= 486.29pf KE= 858.17 KC= 341.14 d33= 365pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	17.15	-203.27	130.31	2234.81	51.80	888.38
100	17.03	-203.33	129.40	2203.65	51.44	875.99
300	16.03	-203.86	121.80	1952.45	48.42	776.14
500	15.68	-204.05	119.14	1868.12	47.36	742.62
700	14.82	-204.54	112.61	1668.82	44.76	663.39
1000	13.98	-205.05	106.22	1485.00	42.23	590.32

Eccogel 1365-25 Matrix and 1365-25 Jacket.
16, 3-1 Machined Safari PZT elements.
Center hole filled wtih Tra-bond 2113 Epoxy.
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.


ECCO 04
* cycle #5
X cycle #6
g_h (x10^{-3}Vm/N)
75
50
25
0
-100
200
500
800
1100
PRESSURE (PSI)

ECCO 05

Cycle 05

C= 541.56pf KE= 955.71 KC= 379.91 d33= 365pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	26.55	-199.48	224.66	5964.78	89.31	2371.10
100	27.94	-199.03	236.42	6605.69	93.98	2625.87
300	27.08	-199.31	229.15	6205.30	91.09	2466.71
500	25.80	-199.73	218.32	5632.55	86.78	2237.03
700	25.66	-199.77	217.13	5571.59	86.31	2214.60
1000	23.80	-200.43	201.39	4793.13	80.06	1905.35

Cycle 06

C= 541.56pf KE= 955.71 KC= 379.91 d33= 365pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	28.68	-198.81	242.69	6960.24	96.47	2766.80
100	28.19	-198.96	238.54	6724.43	94.82	2673.07
300	27.30	-199.24	231.01	6306.54	91.83	2506.95
500	26.90	-199.36	227.62	6123.08	90.48	2434.02
700	25.49	-199.83	215.69	5498.01	85.74	2185.55
1000	24.41	-200.21	206.55	5041.98	82.11	2004.27

Eccogel 1365-45 Matrix and 1365-25 Jacket.
16, 3-1 Machined Safari PZT elements.
Center hole filled with Tra-bond 2113 Epoxy.
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.

ECCO 06

Cycle 01

C= 526.94pf KE= 929.91 KC= 369.65 d33= 350pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	28.80	-198.77	237.12	6829.13	94.26	2714.66
100	29.85	-198.46	245.77	7336.17	97.70	2916.21
300	28.35	-198.91	233.42	6617.39	92.79	2630.49
500	28.25	-198.94	232.59	6570.79	92.46	2611.96
700	26.99	-199.33	222.22	5997.72	88.34	2384.16
1000	25.91	-199.69	213.33	5527.33	84.80	2197.18

Cycle 02

C= 526.94pf KE= 929.91 KC= 369.65 d33= 350pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	30.29	-198.33	249.39	7554.03	99.14	3002.32
100	30.46	-198.28	250.79	7639.07	99.69	3038.62
300	29.50	-198.56	242.89	7165.14	96.55	2848.22
500	28.24	-198.94	232.51	6566.14	92.43	2610.11
700	27.49	-199.18	226.34	6222.00	89.97	2473.32
1000	26.75	-199.41	220.24	5891.53	87.55	2341.95

Eccogel 1365-80 Matrix and 1365-25 Jacket.
16, 3-1 Machined Safari PZT elements.
Center hole filled with Tra-bond 2113 Epoxy.
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.

Cycle 01

C= 526.94pf KE= 929.91 KC= 369.65 d33= 350pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	28.80	-198.77	237.12	6829.13	94.26	2714.66
100	29.85	-198.46	245.77	7336.17	97.70	2916.21
300	28.35	-198.91	233.42	6617.39	92.79	2630.49
500	28.25	-198.94	232.59	6570.79	92.46	2611.96
700	26.99	-199.33	222.22	5997.72	88.34	2384.16
1000	25.91	-199.69	213.33	5527.33	84.80	2197.18

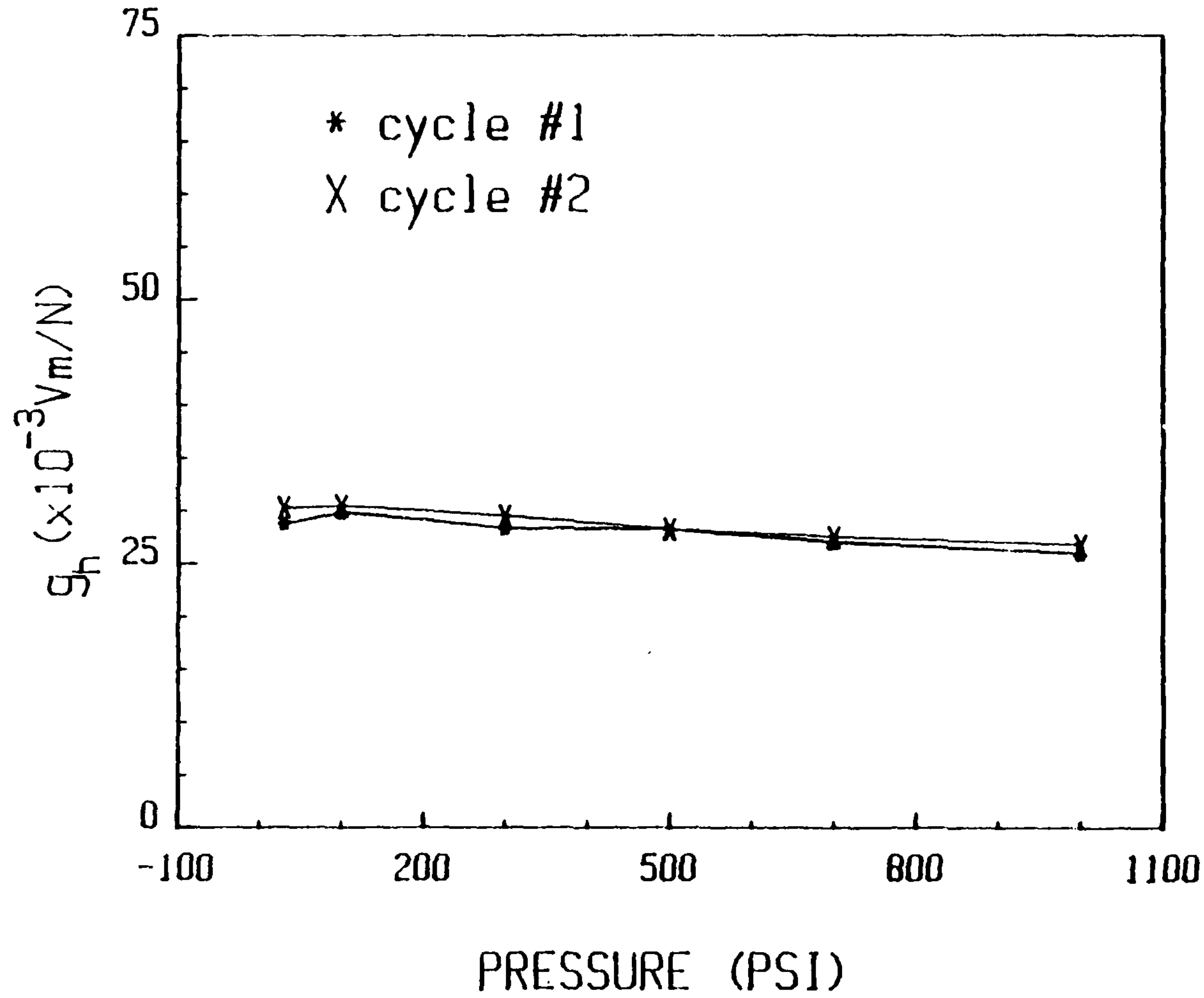
Cycle 02

C= 526.94pf KE= 929.91 KC= 369.65 d33= 350pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	30.29	-198.33	249.39	7554.03	99.14	3002.82
100	30.46	-198.28	250.79	7639.07	99.69	3036.62
300	29.50	-198.56	242.89	7165.14	96.55	2848.22
500	28.24	-198.94	232.51	6566.14	92.43	2610.11
700	27.49	-199.18	226.34	6222.00	89.97	2473.32
1000	26.75	-199.41	220.24	5891.53	87.55	2341.95

Eccogel 1365-80 Matrix and 1365-25 Jacket.
16, 3-1 Machined Safari PZT elements.
Center hole filled with Tra-bond 2113 Epoxy.
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.

ECCO 06



75
50
25
0
-100
200
500
800
1100
* cycle #1
X cycle #2
g_h ($\times 10^{-3}$ Vm/N)
PRESSURE (PSI)

Ecco 07

Cycle 01

C= 545.05pf KE= 961.87 KC= 382.36 d33= 280pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	25.57	-199.80	217.76	5568.23	86.57	2213.47
100	24.75	-200.09	210.78	5216.83	83.79	2073.78
300	22.98	-200.73	195.71	4497.34	77.80	1787.77
500	22.15	-201.05	188.64	4178.34	74.99	1660.96
700	22.15	-201.05	188.64	4178.34	74.99	1660.96
1000	20.29	-201.81	172.80	3506.07	68.69	1393.72

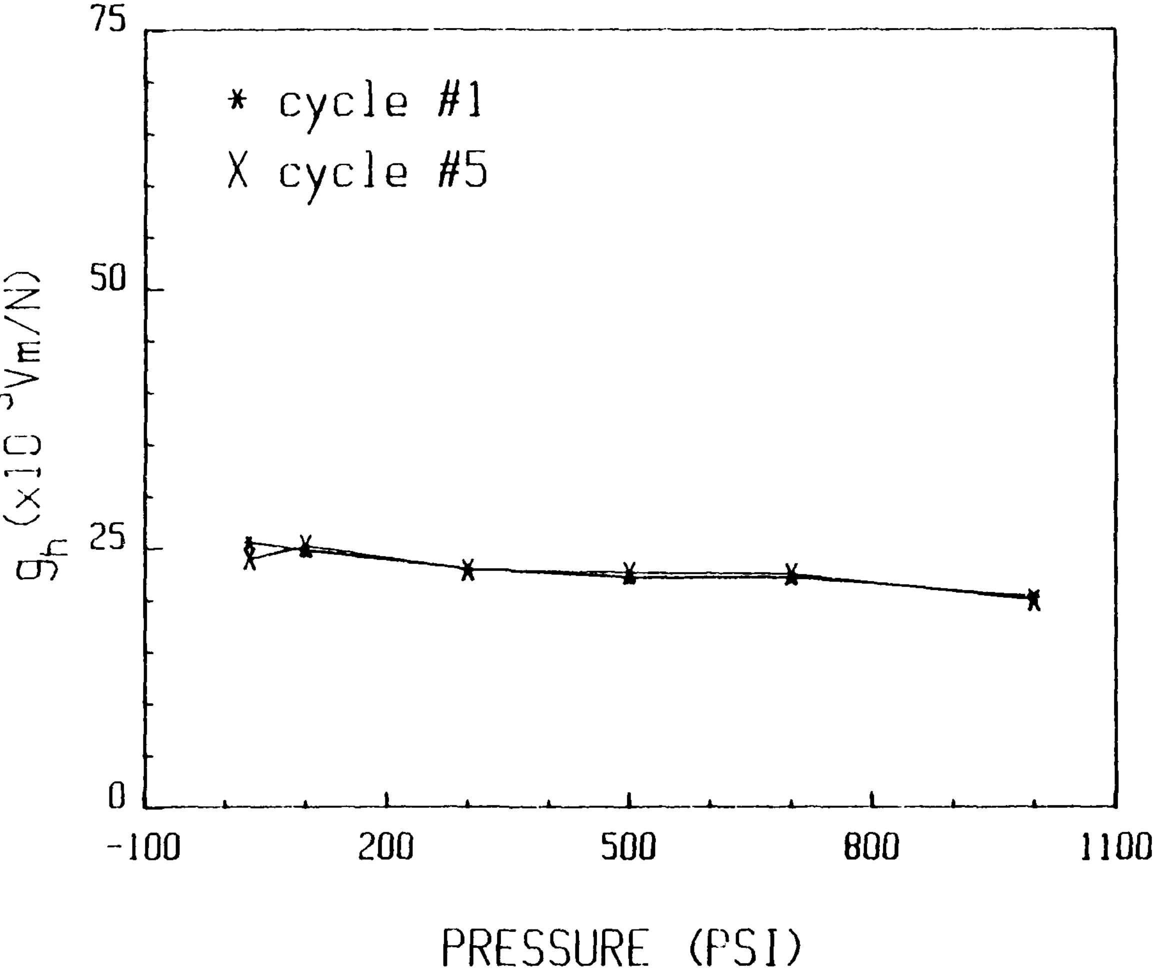
Cycle 05

C= 540.63pf KE= 954.07 KC= 379.26 d33= 280pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	23.99	-200.36	202.65	4861.61	80.56	1932.58
100	25.20	-199.93	212.87	5364.40	84.62	2132.44
300	22.91	-200.76	193.53	4433.74	76.93	1762.49
500	22.61	-200.87	190.99	4318.38	75.92	1716.63
700	22.46	-200.93	189.73	4261.27	75.42	1693.73
1000	19.94	-201.96	168.44	3358.69	66.96	1335.14

Eccogel 1365-0 Matrix and 1365-45 Jacket.
16, 3-1 Machined Safari PZT elements.
Center hole filled with Tra-bond 2113 Epoxy.
Electrode Eccogel 1365.0 + Metz fine silver powder and flake.

ECCO 07



75
50
25
0
* cycle #1
X cycle #5
g_h (x10^{-3}Vm/N)
-100
200
500
800
1100
PRESSURE (PSI)

Cycle 01

C= 527.47pf KE= 930.85 KC= 370.03 d33= 363pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	22.31	-200.99	183.87	4102.21	73.09	1630.71
100	23.32	-200.60	192.20	4482.05	76.40	1781.70
300	21.51	-201.31	177.28	3813.29	70.47	1515.85
500	21.63	-201.26	178.27	3855.96	70.87	1532.81
700	21.20	-201.43	174.73	3704.17	69.46	1472.48
1000	20.98	-201.52	172.91	3627.69	68.74	1442.07

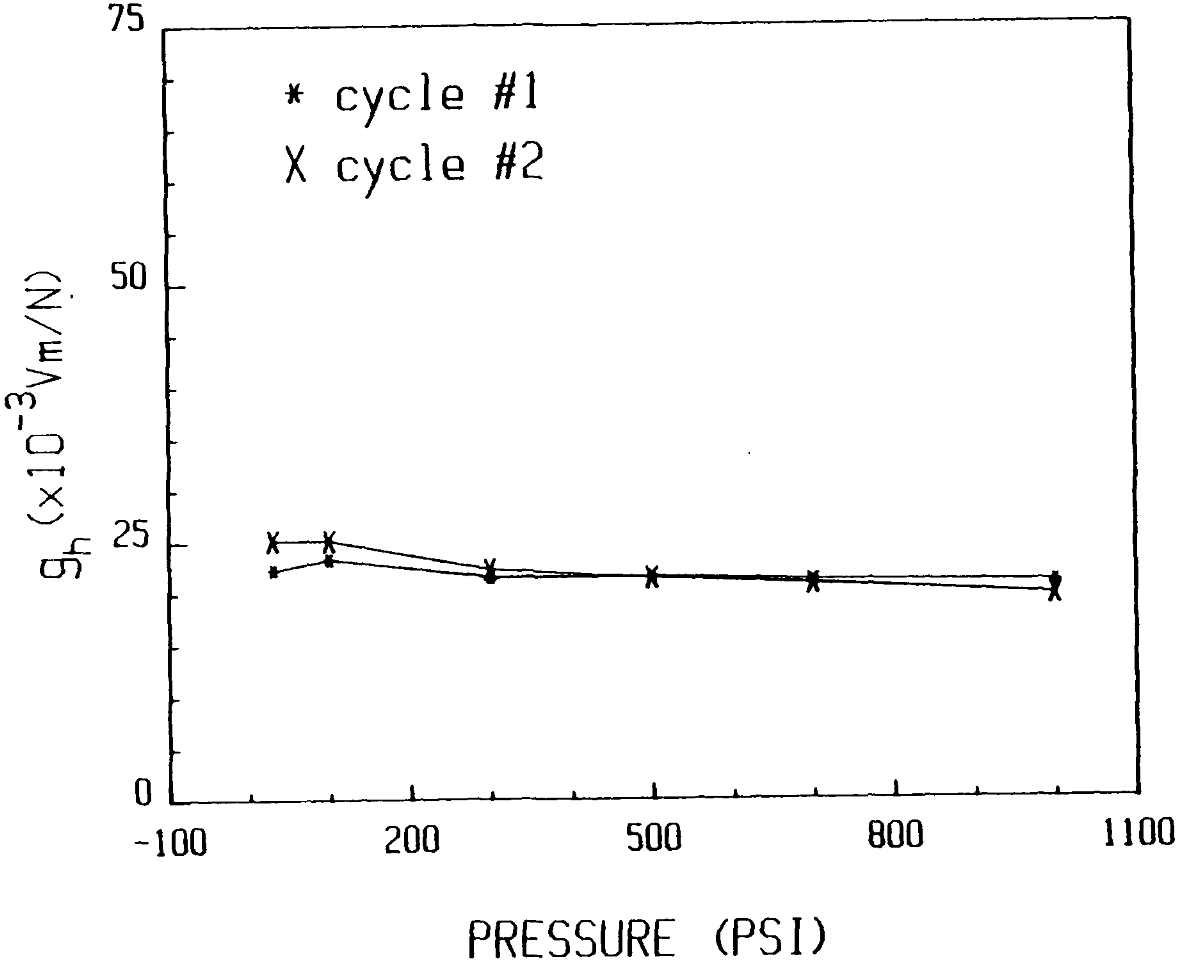
Cycle 02

C= 527.47pf KE= 930.85 KC= 370.03 d33= 363pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	25.18	-199.94	207.53	5225.53	82.50	2077.25
100	25.15	-199.95	207.28	5213.09	82.40	2072.30
300	22.27	-201.00	183.54	4087.52	72.96	1624.06
500	21.45	-201.33	176.79	3792.05	70.28	1507.41
700	20.83	-201.59	171.68	3576.00	68.24	1421.53
1000	19.70	-202.07	162.36	3178.54	64.54	1271.48

Eccogel 1365-25 Matrix and 1365-45 Jacket.
16, 3-1 Machined Safari PZT elements.
Center hole filled with Tra-bond 2113 epoxy.
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.

ECCO 08



* cycle #1
X cycle #2
75
50
25
0
-100
200
500
800
1100
g_h ($\times 10^{-3}$Vm/N)
PRESSURE (PSI)

Cycle 01

C= 529.37pf KE= 934.2 KC= 371.36 d33= 350pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	27.78	-199.08	229.78	6383.28	91.34	2537.46
100	28.31	-198.92	234.16	6629.17	93.08	2635.20
300	27.05	-199.32	223.74	6052.21	88.94	2405.85
500	26.55	-199.48	219.61	5830.54	87.30	2317.73
700	26.54	-199.48	219.52	5826.14	87.26	2315.99
1000	23.98	-200.36	198.35	4756.39	78.85	1890.75

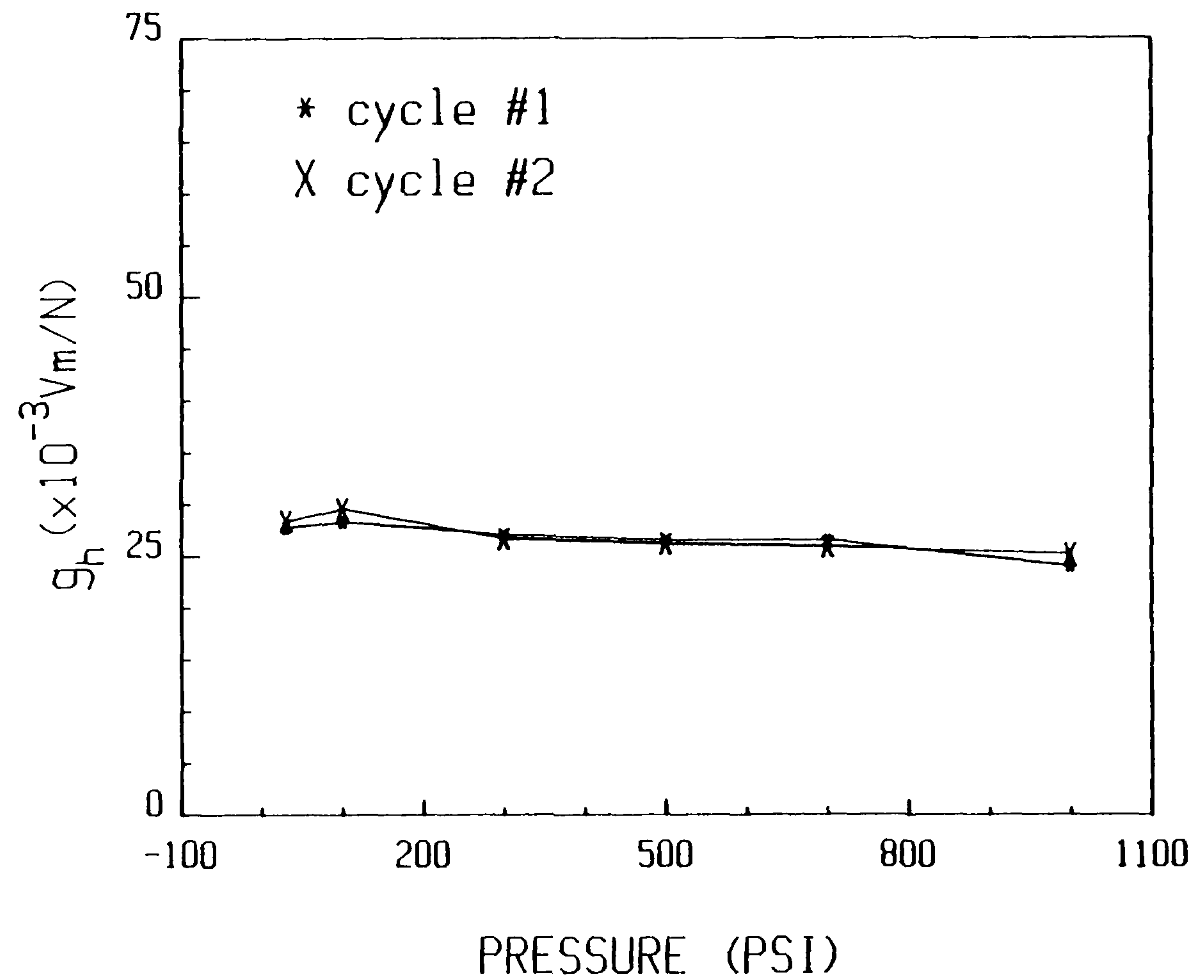
Cycle 02

C= 529.37pf KE= 934.2 KC= 371.36 d33= 350pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	28.39	-198.90	234.83	6666.69	93.35	2650.12
100	29.57	-198.54	244.59	7232.39	97.23	2875.00
300	26.68	-199.44	220.68	5887.77	87.72	2340.49
500	26.18	-199.60	216.55	5667.16	86.08	2253.58
700	25.87	-199.70	213.98	5535.70	85.06	2200.53
1000	25.16	-199.94	208.11	5236.01	82.73	2081.40

Eccogel 1365-45 Matrix and 1365-45 Jacket.
16, 3-1 Machined Safari PZT elements.
Center hole filled with Tra-bond 2113 epoxy.
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.

ECCO 09



75
50
25
0
* cycle #1
X cycle #2
g_h ($\times 10^{-3}$Vm/N)
-100
200
500
800
1100
PRESSURE (PSI)

Cycle 01

C= 540.33pf KE= 954.42 KC= 379.4 d33= 265pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	25.22	-199.92	213.12	5374.89	84.72	2136.62
100	25.68	-199.77	217.01	5572.74	86.26	2215.27
300	25.45	-199.85	215.06	5473.37	85.49	2175.77
500	25.46	-199.84	215.15	5477.67	85.53	2177.48
700	24.65	-200.12	208.30	5134.67	82.80	2041.13
1000	23.90	-200.39	201.97	4826.97	80.29	1918.81

Cycle 02

C= 540.83pf KE= 954.42 KC= 379.4 d33= 265pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	26.59	-199.46	224.70	5974.69	89.32	2375.05
100	26.85	-199.38	226.89	6092.11	90.19	2421.73
300	25.86	-199.71	218.53	5651.14	86.87	2246.44
500	25.64	-199.78	216.67	5555.40	86.13	2208.38
700	24.62	-200.13	208.05	5122.18	82.70	2036.16
1000	23.83	-200.42	201.37	4798.74	80.05	1907.59

Eccogel 1365-80 Matrix and 1365-45 Jacket.
16, 3-1 Machined Safari PZT elements.
Center hole filled with Tra-bond 2113 Epoxy.
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.

AD-A148 260 HINGED HYDROSTATIC TRANSDUCERS(U) PENNSYLVANIA STATE UNIV UNIVERSITY PARK MATERIALS RESEARCH LAB G O DAYTON ET AL. 1984 N00014-82-G-0072 2/2

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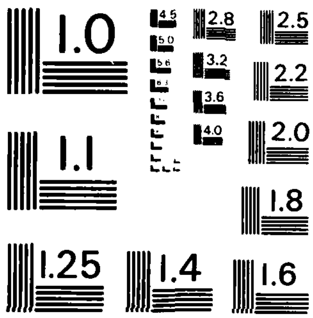
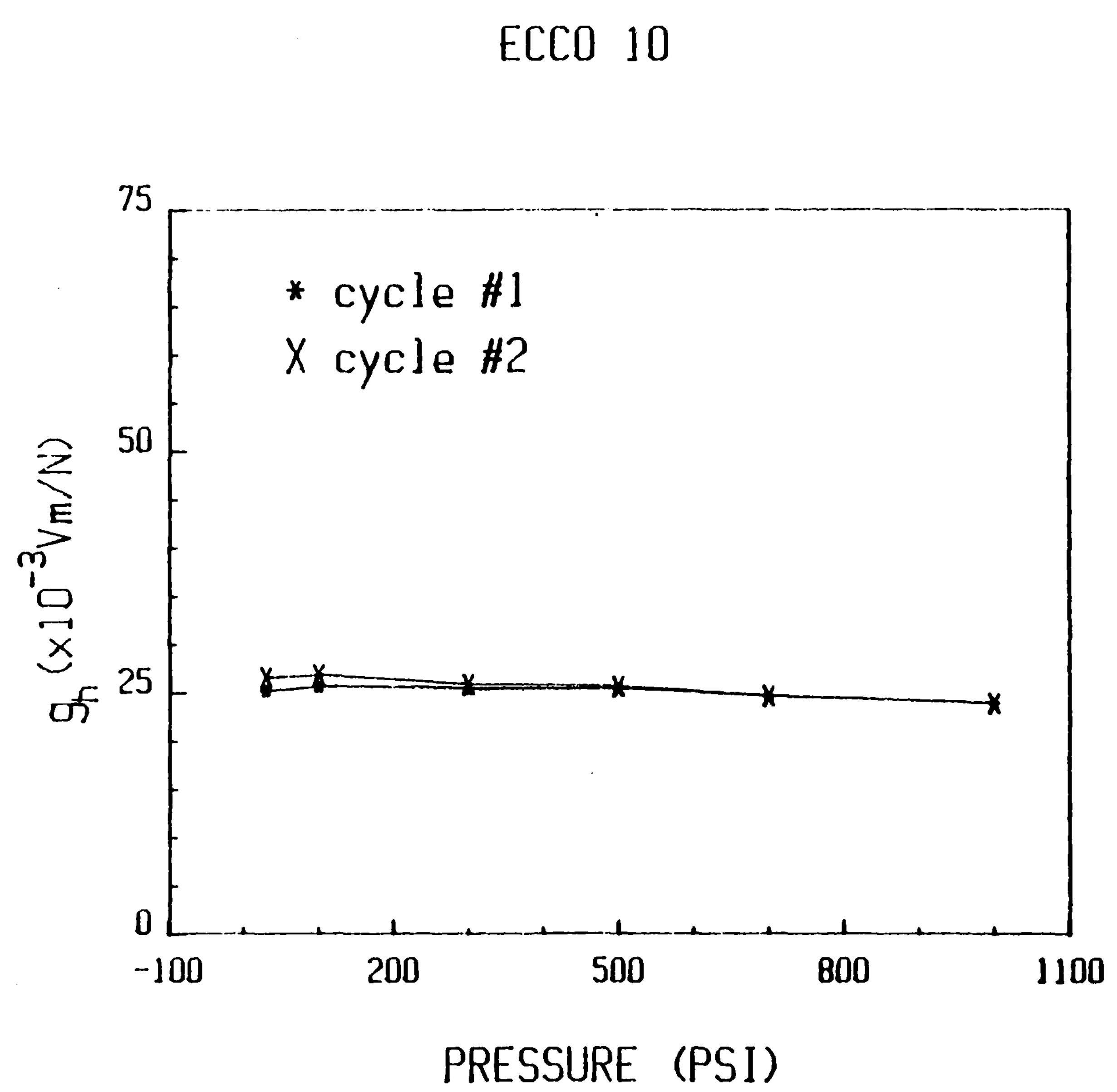


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A


ECCO 10
* cycle #1
X cycle #2
75
50
25
0
-100
200
500
800
1100
g_h ($\times 10^{-3}$ Vm/N)
PRESSURE (PSI)

Cycle 03

C= 886.17pf KE= 1000.87 KC= 621.66 d33= 325pC/N ELMA= 4cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	qh Vm/N	Sens db re 1V/uPa	dh C/N	dhqh m2/N	dh C/N	dhqh m2/N
30	25.21	-199.93	223.40	5632.00	138.76	3498.15
100	26.75	-199.41	237.05	6341.10	147.24	3938.58
300	25.61	-199.79	226.95	5812.14	140.96	3610.04
500	24.41	-200.21	216.31	5280.23	134.36	3279.65
700	24.00	-200.35	212.68	5104.34	132.10	3170.41
1000	22.52	-200.91	199.57	4494.22	123.95	2791.45

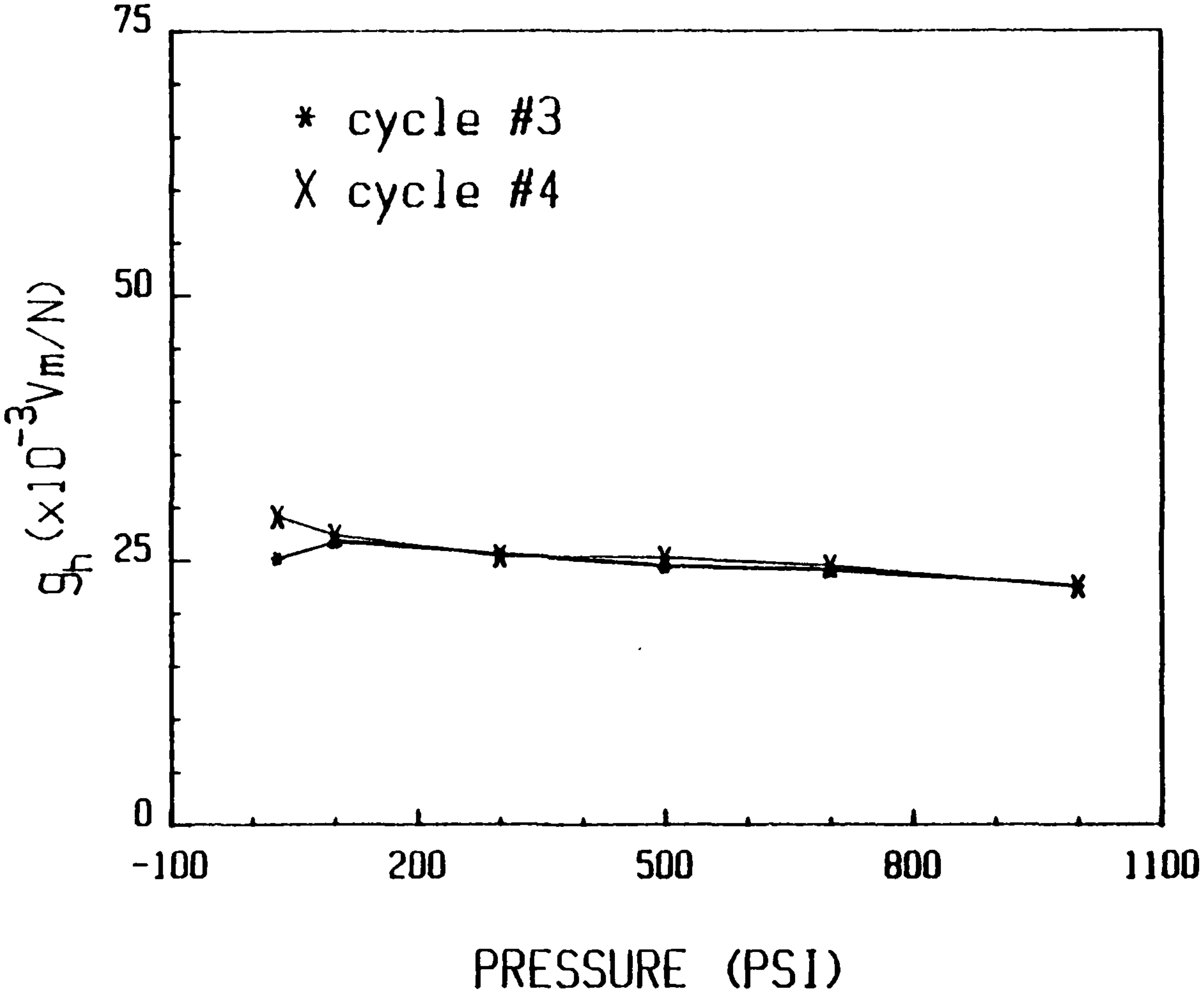
Cycle 04

C= 886.17pf KE= 1000.87 KC= 621.66 d33= 325pC/N ELMA= 4cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	qh Vm/N	Sens db re 1V/uPa	dh C/N	dhqh m2/N	dh C/N	dhqh m2/N
30	29.17	-198.66	258.50	7540.32	160.56	4683.44
100	27.35	-199.22	242.37	6628.75	150.54	4117.25
300	25.44	-199.85	225.44	5735.24	140.03	3562.27
500	25.26	-199.91	223.85	5654.37	139.04	3512.04
700	24.45	-200.17	216.67	5297.55	134.58	3290.41
1000	22.51	-200.91	199.48	4490.23	123.90	2780.97

Eccogel 1365-0 Matrix and 1365-25 Jacket.
25, 3-1 Machined Safari PZT elements.
Center hole filled with Tra-bond 2113 epoxy.
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.

ECCO 11



75
50
25
0
* cycle #3
X cycle #4
g_h ($\times 10^{-3}$ Vm/N)
-100
200
500
800
1100
PRESSURE (PSI)

Cycle 01

C= 874.11pf KE= 987.25 KC= 613.2 d33= 325pC/N ELMA= 4cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	26.73	-199.42	233.65	6245.46	145.12	3879.18
100	28.80	-198.77	251.74	7250.23	156.36	4503.26
300	28.07	-198.99	245.36	6887.34	152.40	4277.86
500	26.72	-199.42	233.56	6240.79	145.07	3876.27
700	26.39	-199.53	230.68	6087.59	143.28	3781.12
1000	25.72	-199.75	224.82	5782.41	139.64	3591.56

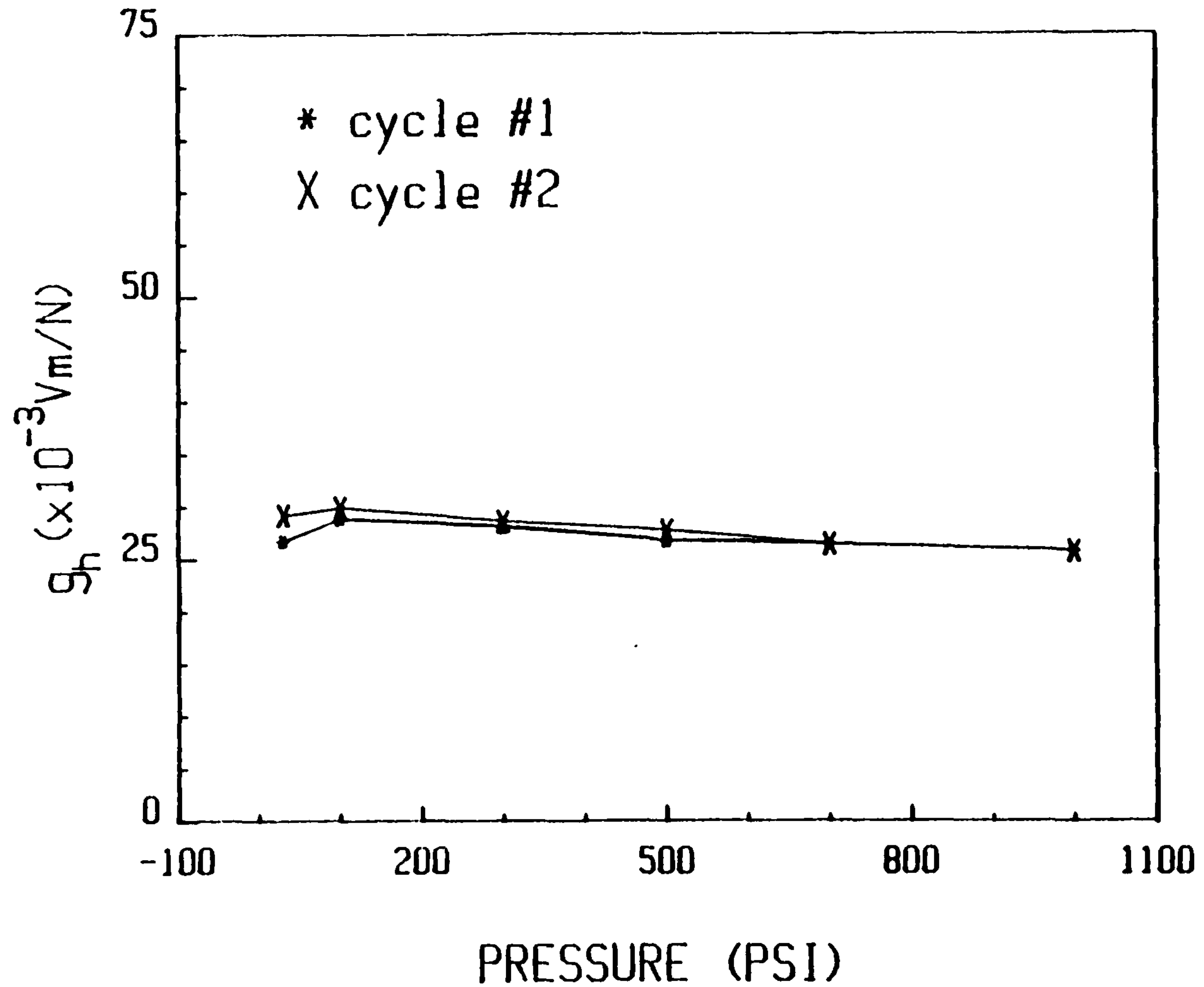
Cycle 02

C= 874.11pf KE= 987.25 KC= 613.2 d33= 325pC/N ELMA= 4cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	29.19	-198.65	255.15	7447.92	158.48	4626.05
100	29.89	-198.45	261.27	7809.41	162.28	4850.56
300	28.59	-198.83	249.91	7144.88	155.22	4437.82
500	27.68	-199.12	241.95	6697.29	150.28	4159.81
700	26.37	-199.54	230.50	6078.37	143.17	3775.39
1000	25.68	-199.77	224.47	5764.43	139.42	3580.40

Eccogel 1365-25 Matrix and 1365-45 Jacket.
25, 3-1 Machined Safari PZT elements.
Center hole filled with Tra-bond 2113 epoxy.
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.

ECCO 12



75
50
25
0
* cycle #1
X cycle #2
g_h (x10^{-3}Vm/N)
-100
200
500
800
1100
PRESSURE (PSI)

Cycle 01

C= 848.98pf KE= 958.87 KC= 595.57 d33= 350pC/N ELMA= 4cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	29.12	-198.67	247.22	7199.16	153.55	4471.52
100	29.44	-198.58	249.94	7358.26	155.24	4570.33
300	28.53	-198.85	242.21	6910.39	150.44	4292.16
500	27.89	-199.05	236.78	6603.34	147.07	4101.75
700	26.71	-199.43	226.76	6056.85	140.85	3762.01
1000	26.35	-199.54	223.71	5894.68	138.95	3661.29

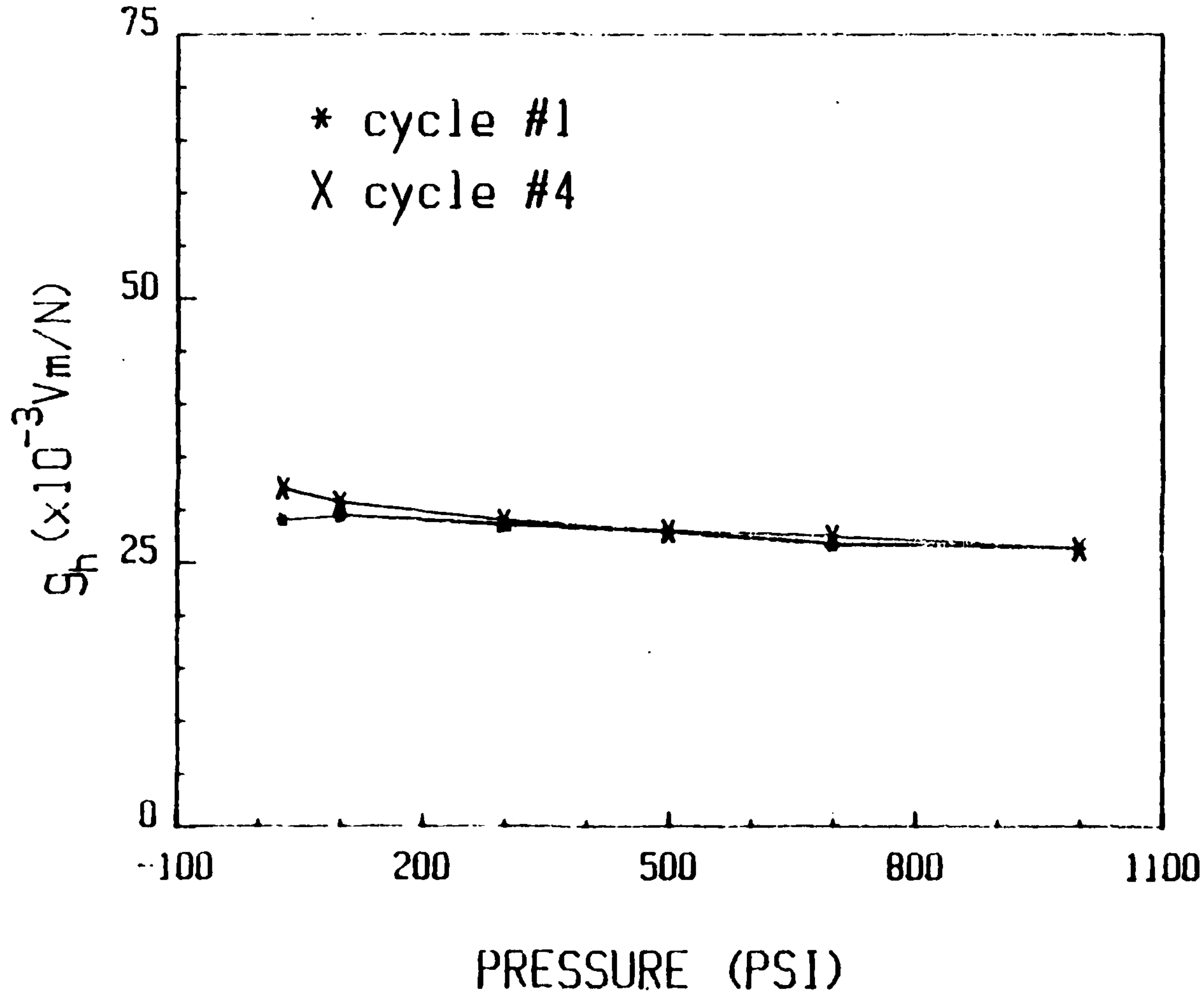
Cycle 04

C= 849.38pf KE= 959.32 KC= 595.85 d33= 350pC/N ELMA= 4cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	32.03	-197.85	272.06	8713.99	168.98	5412.41
100	30.67	-198.22	260.51	7989.70	161.80	4962.54
300	28.95	-198.73	245.90	7118.69	152.73	4421.54
500	27.97	-199.02	237.57	6644.89	147.56	4127.26
700	27.44	-199.19	233.07	6395.45	144.76	3972.32
1000	26.27	-199.57	223.13	5861.69	138.59	3640.80

Eccogel 1365-45 Matrix and 1365-45 Jacket.
25, 3-1 Machined Safari PZT elements.
Center hole filled with Tra-Bond 2113 epoxy.
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.

ECCO 13



75
50
25
0
-100
200
500
800
1100
* cycle #1
X cycle #4
g_h ($\times 10^{-3}$ Vm/N)
PRESSURE (PSI)

ECCO 14

Cycle 03

C= 521.88pf KE= 920.98 KC= 366.1 d33= 313pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	25.42	-199.86	207.28	5269.15	82.40	2094.55
100	27.73	-199.10	226.12	6270.32	89.89	2492.52
300	26.22	-199.59	213.81	5606.03	84.99	2228.46
500	25.35	-199.88	206.71	5240.17	82.17	2083.03
700	24.58	-200.15	200.43	4926.67	79.67	1958.41
1000	24.11	-200.31	196.60	4740.06	78.15	1884.23

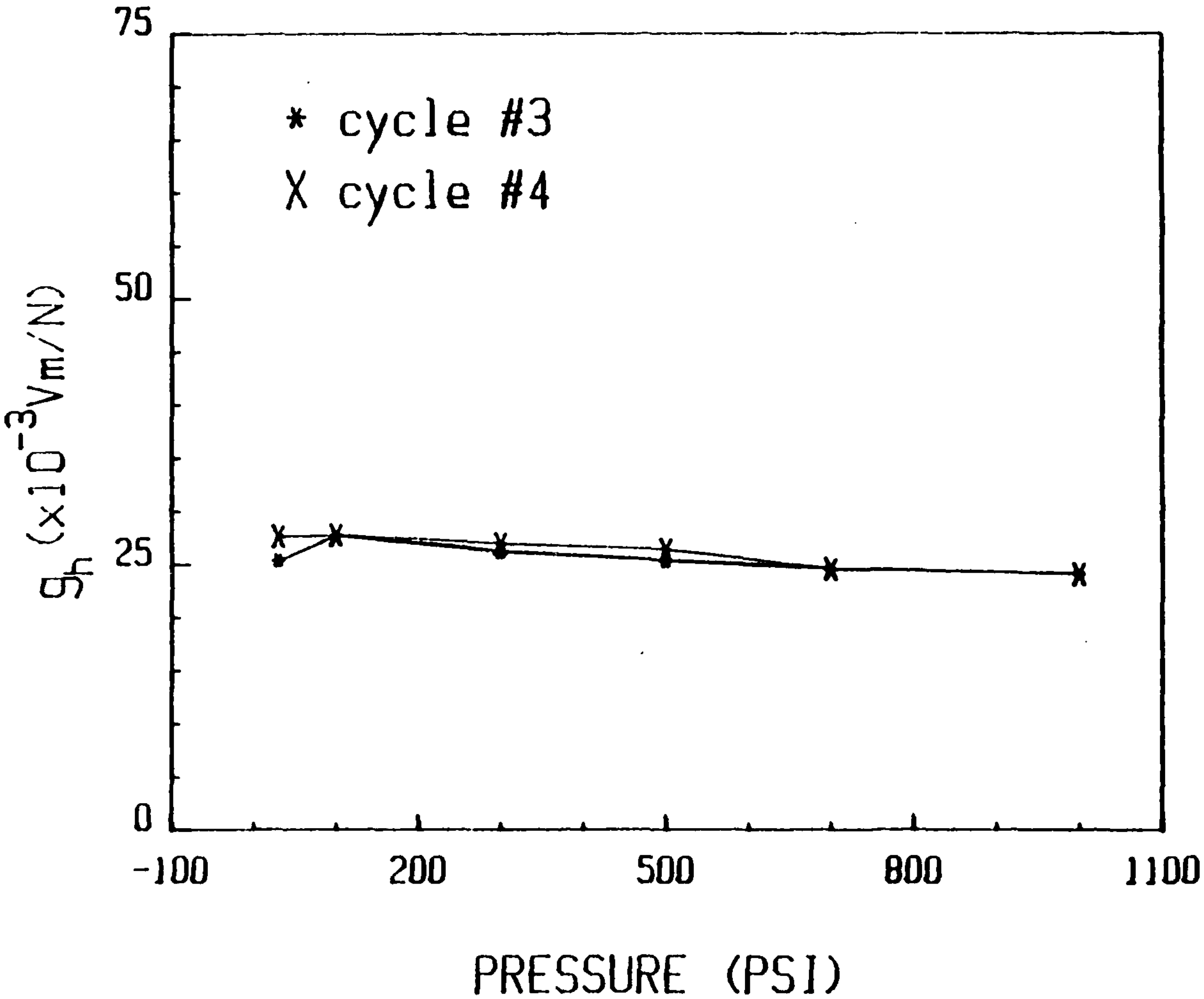
Cycle 04

C= 521.88pf KE= 920.98 KC= 366.1 d33= 313pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	27.68	-199.12	225.71	6247.72	89.72	2483.54
100	27.80	-199.08	226.69	6302.01	90.11	2505.12
300	26.99	-199.33	220.09	5940.12	87.49	2361.27
500	26.41	-199.52	215.36	5687.57	85.61	2260.87
700	24.59	-200.14	200.52	4930.68	79.71	1960.00
1000	24.11	-200.31	196.60	4740.06	78.15	1884.23

Eccogel 1365-25 + 30% P.M.M. (poly methyl methacrylate) Matrix and 1365-25 Jacket.
16, 3-1 Machined Safari PZT elements.
Center hole filled with Tra-bond 2113 epoxy.
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.

ECCO 14



* cycle #3
X cycle #4
75
50
25
0
g_h (x10^{-3}Vm/N)
-100
200
500
800
1100
PRESSURE (PSI)

ECCO 15

Cycle 01

C= 557.32pf KE= 983.37 KC= 390.97 d33= 265pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	25.28	-199.90	220.11	5564.30	87.51	2212.26
100	25.88	-199.70	225.33	5831.56	89.59	2318.52
300	24.98	-200.01	217.49	5433.02	86.47	2160.07
500	25.37	-199.87	220.89	5603.99	87.82	2228.04
700	26.12	-199.62	227.42	5940.22	90.42	2361.73
1000	23.94	-200.38	208.44	4990.05	82.87	1983.95

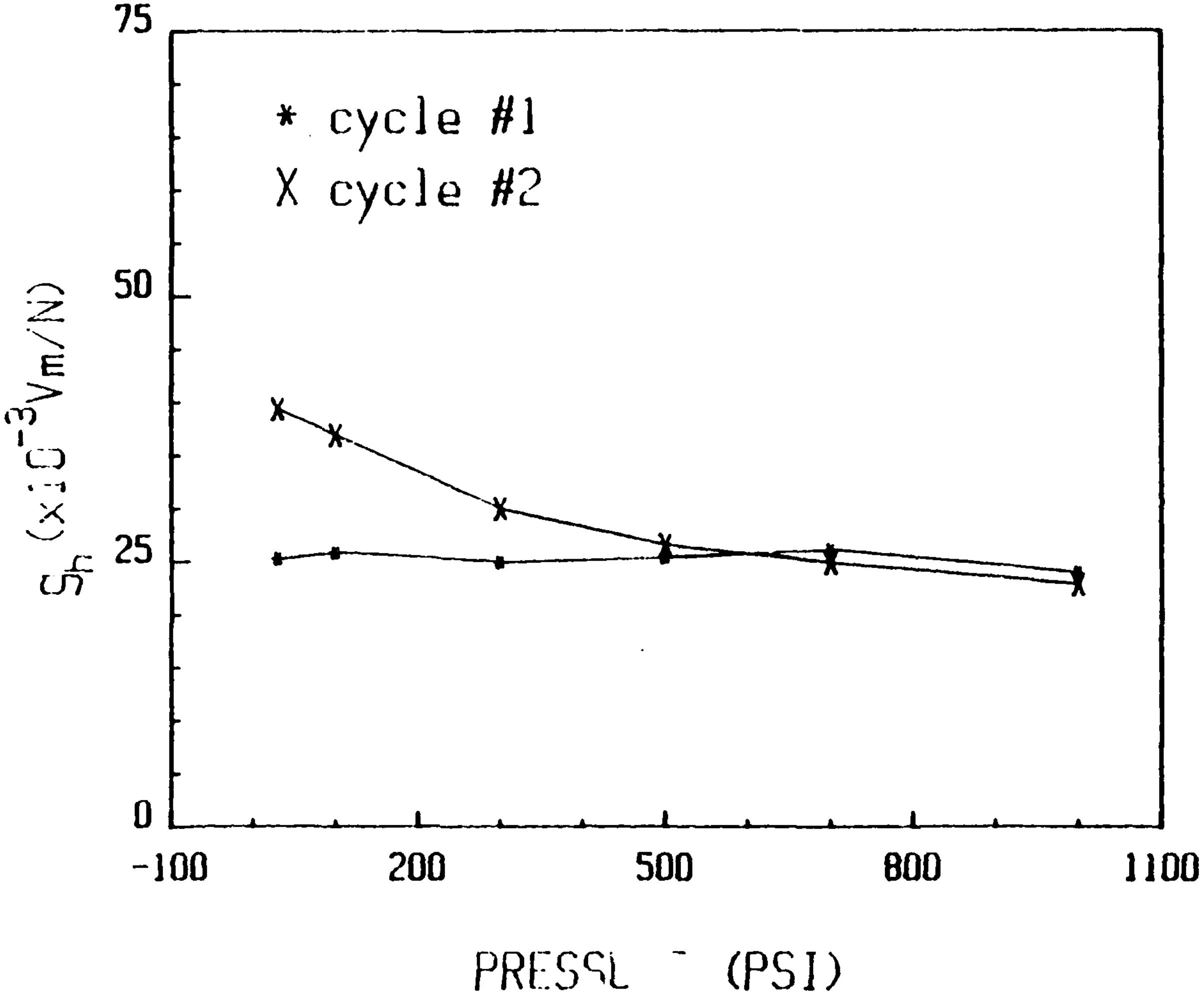
Cycle 02

C= 557.32pf KE= 983.37 KC= 390.97 d33= 265pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	39.34	-196.06	342.52	13474.89	136.18	5357.37
100	36.92	-196.61	321.45	11868.06	127.80	4718.53
300	29.97	-198.43	260.94	7820.42	103.75	3109.26
500	26.53	-199.48	230.99	6128.17	91.84	2436.45
700	24.86	-200.05	216.45	5380.95	86.06	2139.37
1000	22.86	-200.78	199.04	4549.97	79.13	1808.99

Eccogel 1365-25 + 40% M.M. (micro ballons) Matrix and 1365-25 Jacket.
16, 3-1 Machined Safari PZT elements.
Center hole filled with Tra-Bond 2113 epoxy.
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.

ECCO 15


* cycle #1
X cycle #2
75
50
25
0
S_h ($x10^{-3}$Vm/N)
-100
200
500
800
1100
PRESSURE (PSI)

Cycle 01

C= 98.57pf KE= 111.34 KC= 69.15 d33= 190pC/N ELMA= 4cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	31.72	-197.93	31.27	991.88	19.42	616.02
100	36.36	-196.75	35.84	1303.28	22.26	807.43
300	35.66	-196.92	35.15	1253.58	21.83	778.56
500	34.98	-197.08	34.48	1206.23	21.42	749.15
700	35.24	-197.02	34.74	1224.23	21.58	760.33
1000	35.26	-197.01	34.76	1225.62	21.59	761.20

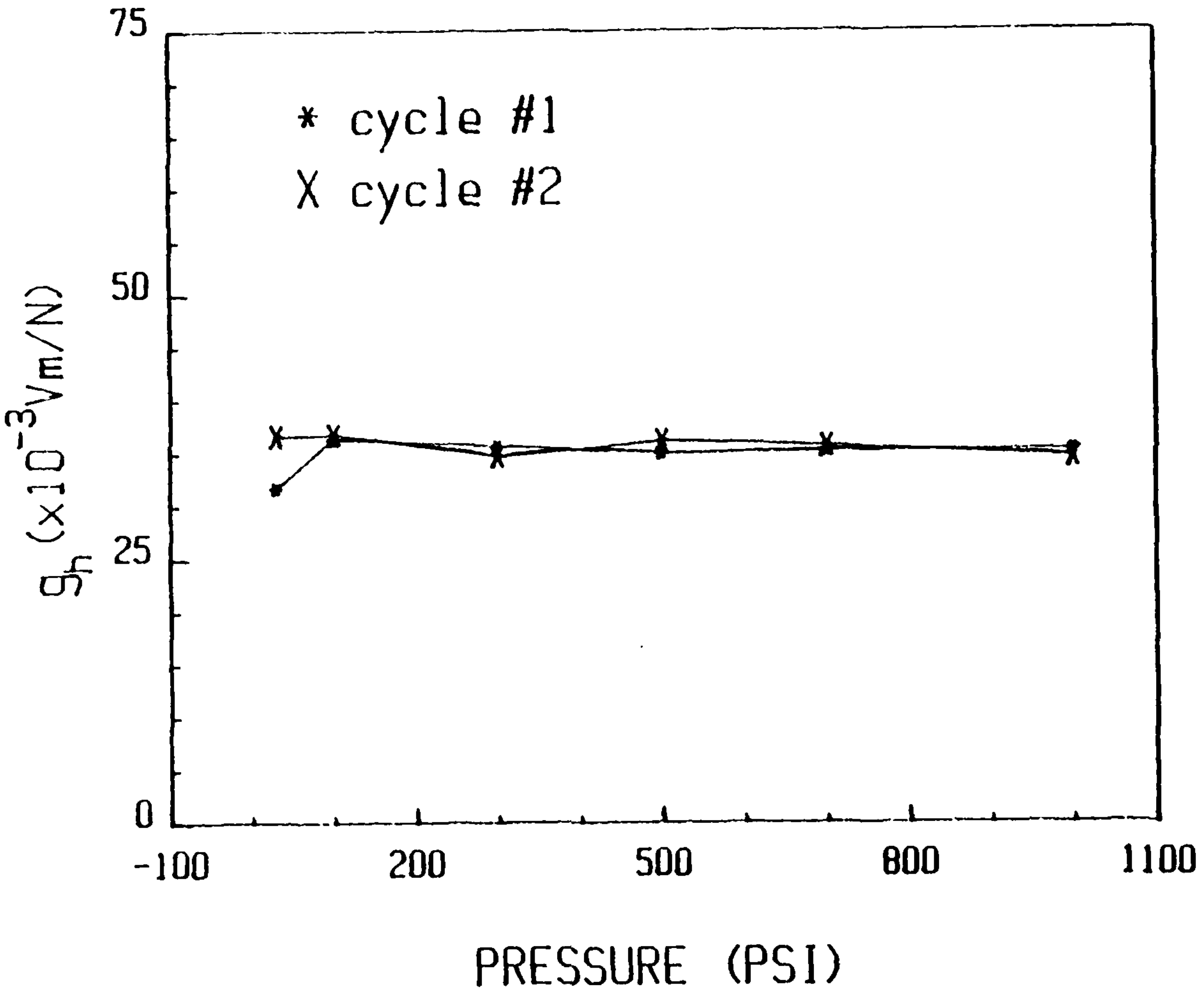
Cycle 02

C= 98.57pf KE= 111.34 KC= 69.15 d33= 190pC/N ELMA= 4cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	36.67	-196.67	36.15	1325.60	22.45	823.29
100	36.79	-196.64	36.27	1334.29	22.52	828.69
300	34.74	-197.14	34.25	1189.74	21.27	738.71
500	36.13	-196.80	35.62	1286.85	22.12	799.22
700	35.62	-196.92	35.11	1250.77	21.81	776.82
1000	34.57	-197.18	34.08	1178.12	21.17	731.70

Eccogel 1365-25 Matrix and 1365-45 Jacket.
25, 1-3 REN 18mil PZT rod elements.
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.

ECCO 16



* cycle #1
X cycle #2
75
50
25
0
g_h (x10^{-3}Vm/N)
-100
200
500
800
1100
PRESSURE (PSI)

Cycle 01

C= 94.5pf KE= 106.73 KC= 66.29 d33= 182pC/N ELMA= 4cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	28.73	-198.79	27.15	780.00	16.86	484.46
100	36.43	-196.73	34.43	1254.14	21.38	778.94
300	34.47	-197.21	32.57	1122.82	20.23	697.38
500	35.70	-196.91	33.74	1204.38	20.95	748.04
700	35.03	-197.07	33.10	1159.59	20.56	720.22
1000	34.36	-197.24	32.47	1115.66	20.17	692.94

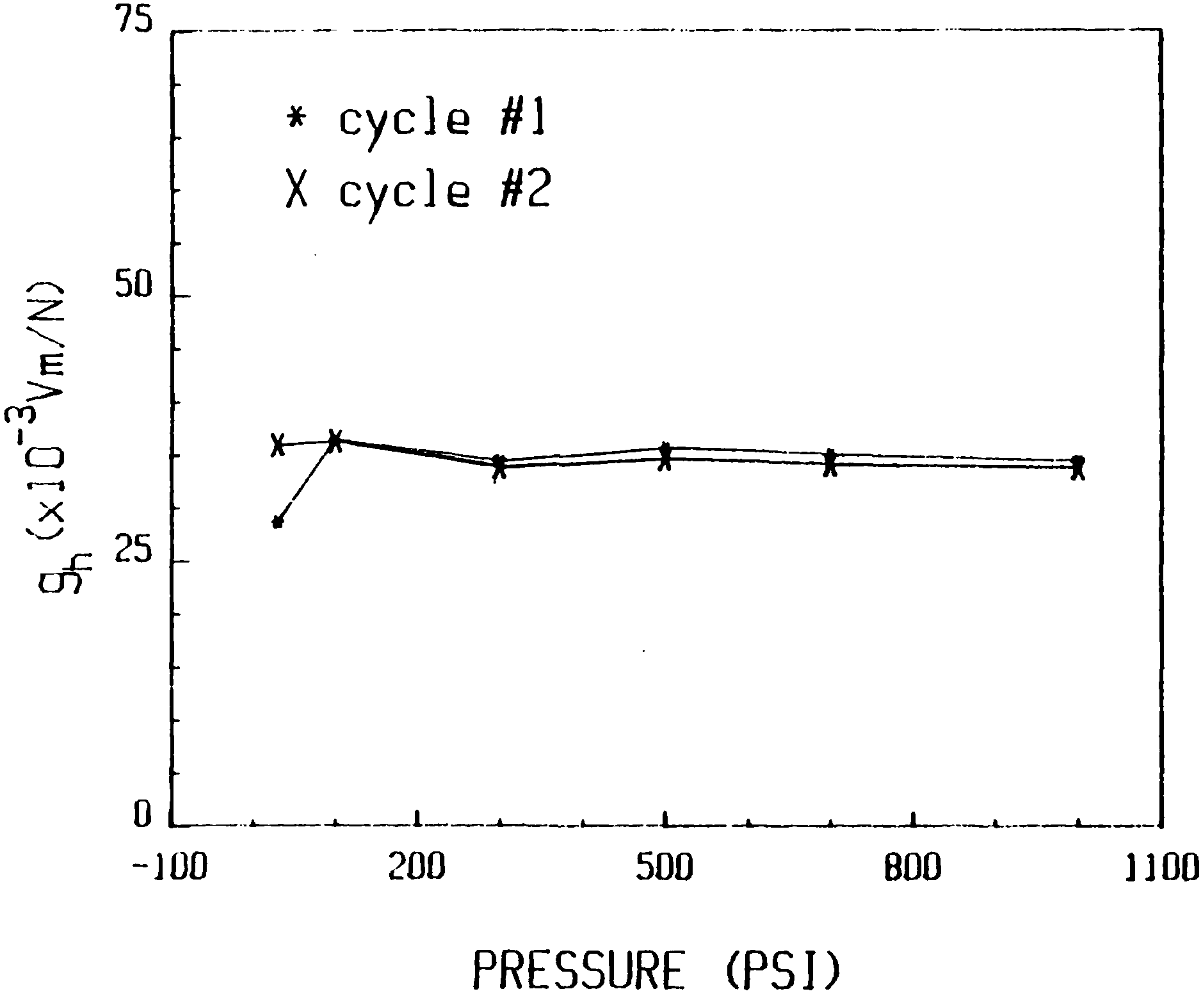
Cycle 02

C= 94.5pf KE= 106.73 KC= 66.29 d33= 182pC/N ELMA= 4cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	35.94	-196.85	33.96	1220.62	21.09	758.13
100	36.27	-196.77	34.27	1243.14	21.29	772.12
300	33.81	-197.38	31.95	1080.23	19.84	670.93
500	34.62	-197.17	32.72	1132.61	20.32	703.46
700	34.04	-197.32	32.17	1094.98	19.98	680.09
1000	33.68	-197.41	31.83	1071.94	19.77	665.73

Eccogel 1365-45 Matrix and 1365-45 Jacket.
25, 1-3 REN 18mil PZT rod elements.
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.

ECCO 17



75
50
25
0
* cycle #1
X cycle #2
g_h ($\times 10^{-3}$ Vm/N)
-100
200
500
800
1100
PRESSURE (PSI)

ECCO 18

Cycle 01

C= 339.54pf KE= 383.49 KC= 238.19 d33= 208pC/N ELMA= 4cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	20.08	-201.90	68.18	1369.06	42.35	850.34
100	15.83	-203.97	53.75	850.85	33.38	528.48
300	17.44	-203.13	59.22	1032.73	36.78	641.44
500	17.63	-203.03	59.86	1055.35	37.18	655.49
700	17.46	-203.12	59.28	1035.10	36.82	642.91
1000	16.61	-203.55	56.40	936.77	35.03	581.84

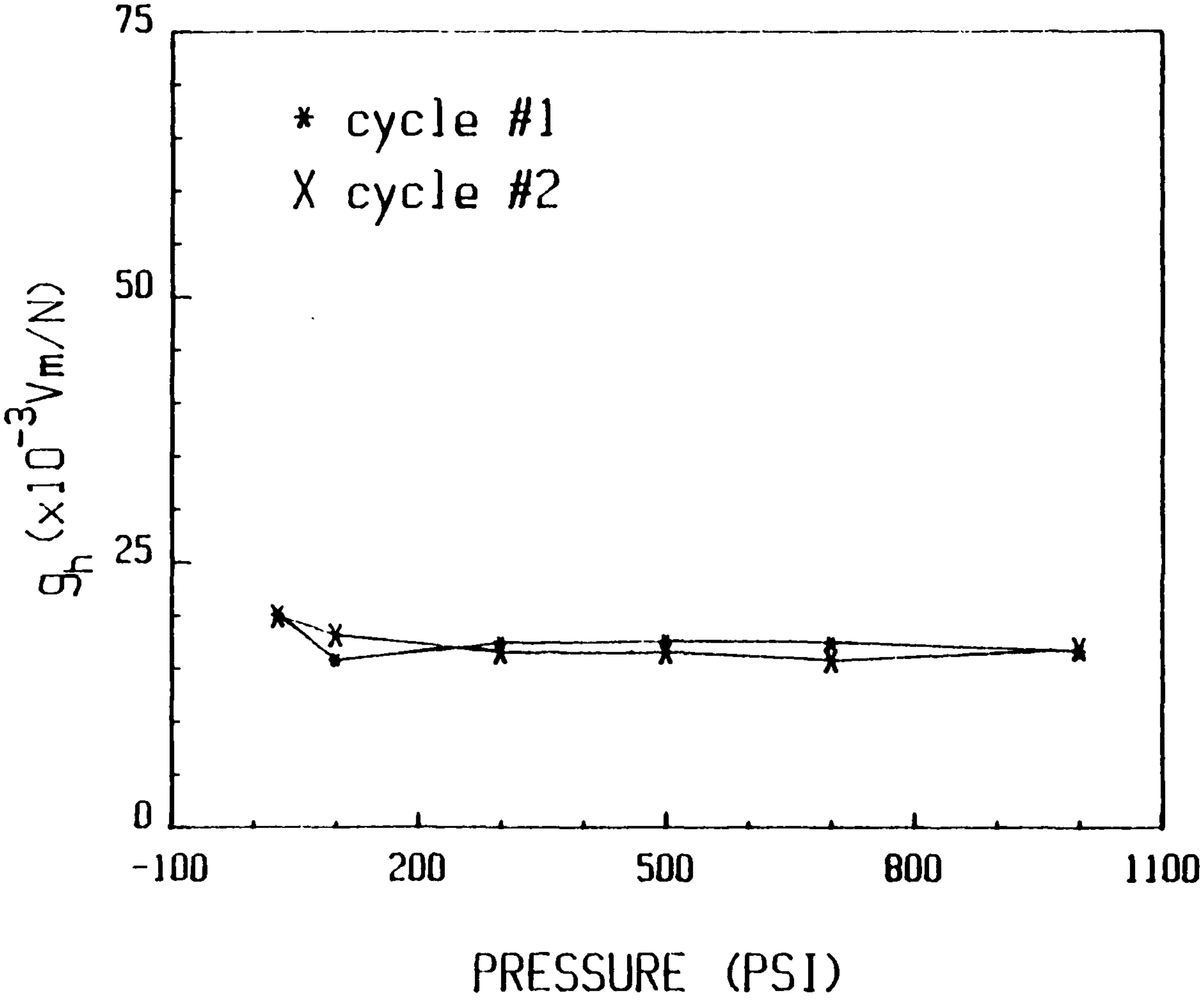
Cycle 02

C= 339.54pf KE= 383.49 KC= 238.19 d33= 208pC/N ELMA= 4cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	19.96	-201.96	67.77	1352.74	42.09	840.20
100	18.17	-202.77	61.69	1120.99	38.32	696.26
300	16.54	-203.57	56.16	928.89	34.88	576.94
500	16.56	-203.58	56.23	931.14	34.92	578.34
700	15.80	-203.99	53.65	847.63	33.32	526.47
1000	16.90	-203.40	57.38	969.77	35.64	602.33

Eccogel 1365-25 Matrix and 1365-45 Jacket.
25, 3-3 Burps
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.

ECCO 18



* cycle #1
X cycle #2
75
50
25
0
g_h (x10^{-3}Vm/N)
-100
200
500
800
1100
PRESSURE (PSI)

ECCO 19

Cycle 01

C= 367.9pf KE= 415.47 KC= 258.08 d33= 215pC/N ELMA= 4cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	19.55	-202.14	71.92	1405.96	44.67	873.35
100	17.82	-202.94	65.55	1168.14	40.72	725.62
300	17.40	-203.15	64.01	1113.72	39.76	691.82
500	17.58	-203.06	64.67	1136.89	40.17	706.21
700	16.96	-203.37	62.39	1058.11	38.75	657.27
1000	16.73	-203.49	61.54	1029.61	38.23	639.57

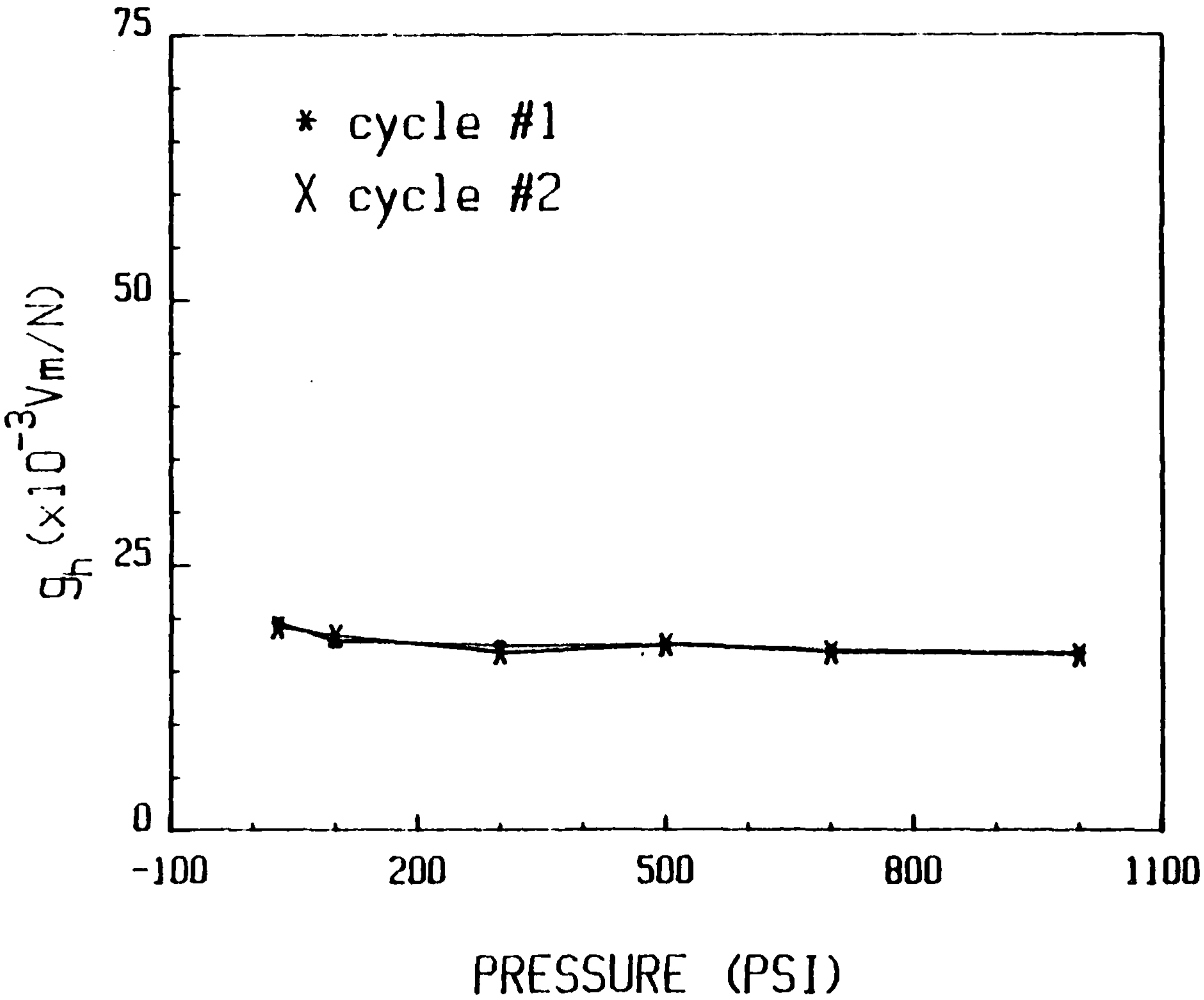
Cycle 02

C= 367.9pf KE= 415.47 KC= 258.08 d33= 215pC/N ELMA= 4cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	19.17	-202.31	70.52	1351.83	43.80	839.73
100	18.38	-202.67	67.61	1242.71	42.00	771.94
300	16.78	-203.46	61.73	1035.77	38.34	643.40
500	17.50	-203.10	64.37	1126.56	39.99	699.79
700	16.78	-203.46	61.73	1035.77	38.34	643.40
1000	16.54	-203.59	60.84	1006.35	37.79	625.12

Eccogel 1365-45 Matrix and 1365-45 Jacket.
25, 3-3 Burps.
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.

ECCO 19



75
50
25
0
g_h ($\times 10^{-3}$ Vm/N)
-100
200
500
800
1100
PRESSURE (PSI)
* cycle #1
X cycle #2

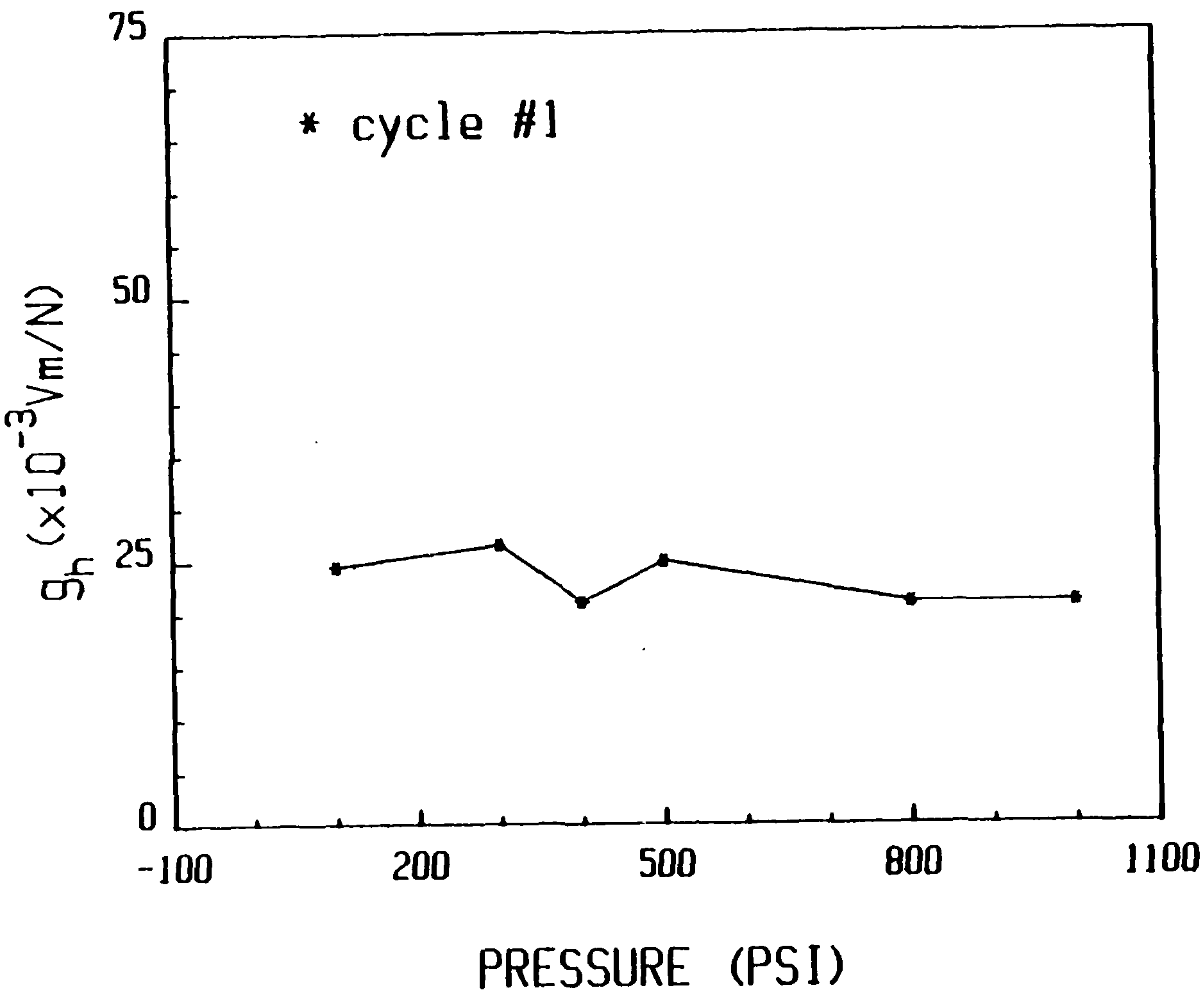
Cycle 01

C= 542pf   KE= 956.49   KC= 380.22   d33= 420pC/N   ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
100	24.54	-200.16	207.82	5099.99	82.61	2027.33
300	26.57	-199.47	225.02	5978.65	89.45	2376.61
400	21.14	-201.46	179.03	3784.69	71.17	1504.47
500	24.98	-200.01	211.55	5284.51	84.09	2100.68
800	20.99	-201.52	177.76	3731.17	70.66	1483.20
1000	20.99	-201.52	177.76	3731.17	70.66	1483.20

Flexane #60 Matrix and #30 Jacket.
16, 3-1 Extruded Safari PZT elements.
Center hole filled with fiber frax.
Electrode Flexane #30 + 45% VME carbon fiber.

FLEX 20



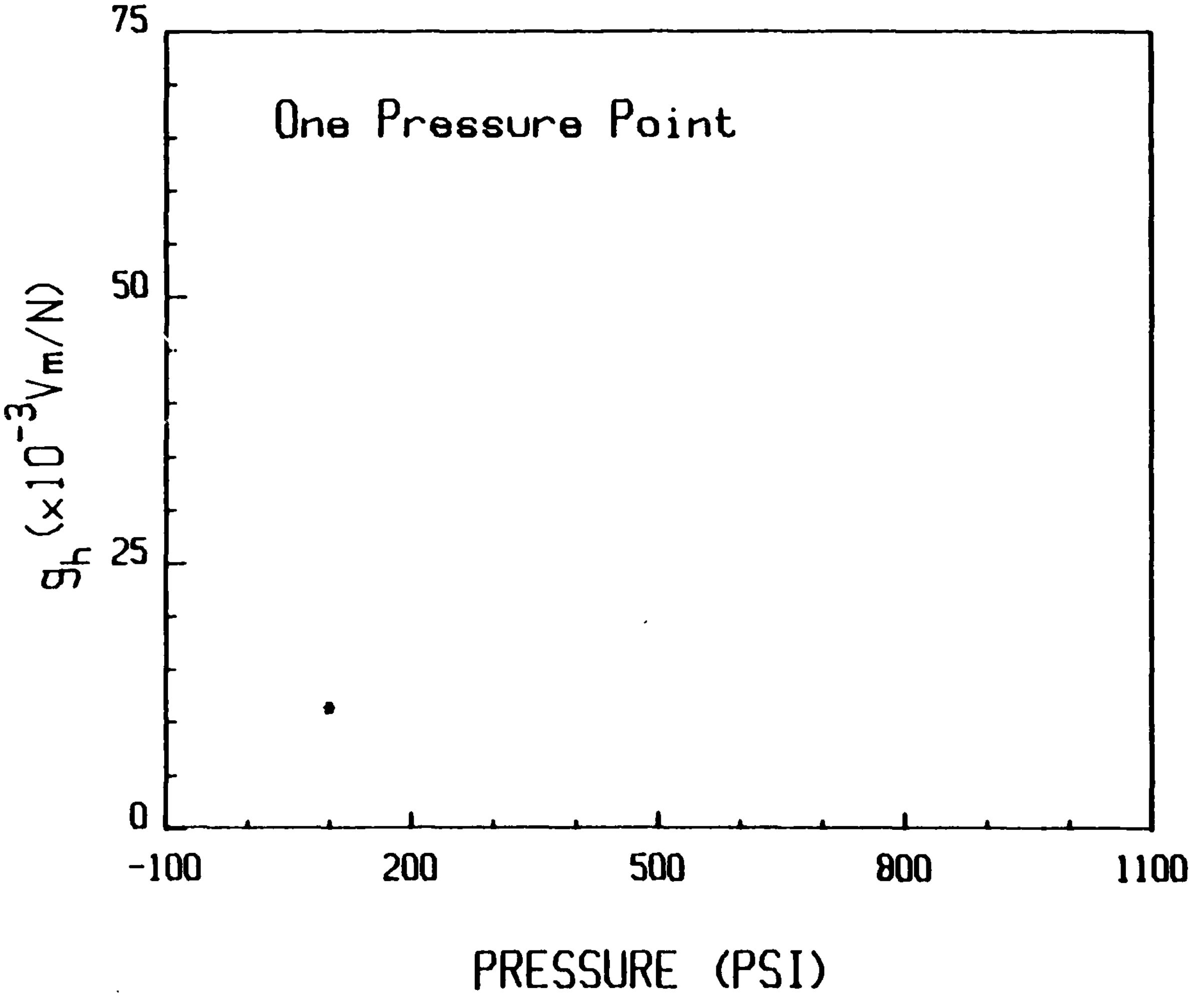
Cycle 01

C= 473.7pf KE= 835.96 KC= 332.31 d33= 400pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
100	11.40	-206.82	84.38	961.91	33.54	382.38

Flexane #30 Matrix and #30 Jacket.
16, 3-1 Extruded Safari PZT elements.
Center hole filled with fiber frax.
Electrode Flexane #30 + 45% VME carbon fiber.

FLEX 21



One Pressure Point
g_h $(\times 10^{-3} V_m/N)$
75
50
25
0
-100
200
500
800
1100
PRESSURE (PSI)

FLEX 22

Cycle 01

C= 537.6pf KE= 948.72 KC= 377.13 d33= 420pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
100	11.68	-206.61	98.11	1145.94	39.00	455.53
300	12.23	-206.21	102.73	1256.41	40.84	499.44
500	11.00	-207.13	92.40	1016.40	36.73	404.03
800	10.74	-207.34	90.22	968.92	35.86	385.16
1000	9.30	-208.59	78.12	726.51	31.05	288.80

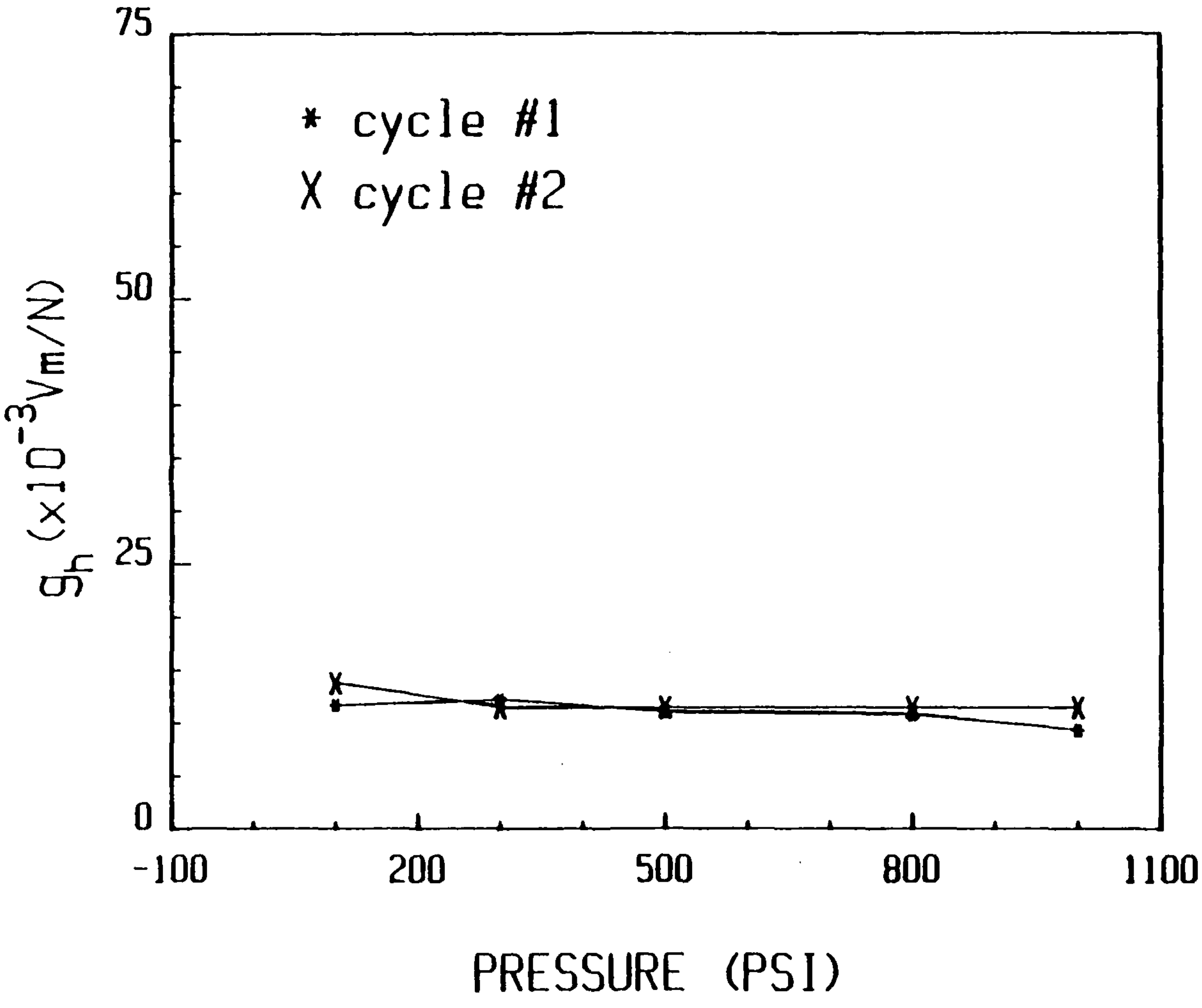
Cycle 02

C= 537.6pf KE= 948.72 KC= 377.13 d33= 420pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
100	13.76	-205.17	115.58	1590.43	45.95	632.22
300	11.46	-206.78	96.26	1103.18	38.27	438.53
500	11.46	-206.78	96.26	1103.18	38.27	438.53
800	11.45	-206.78	96.18	1101.26	38.23	437.77
1000	11.45	-206.78	96.18	1101.26	38.23	437.77

Flexane #60 Matrix and #30 Jacket.
16, 3-1 Extruded Safari PZT elements.
Center hole filled with fiber frax.
Electrode Flexane #30 + 45% VME Carbon fiber.

FLEX 22



75
50
25
0
* cycle #1
X cycle #2
g_h (x10^{-3}Vm/N)
-100
200
500
800
1100
PRESSURE (PSI)

Cycle 01

C= 523.6pf KE= 924.02 KC= 367.31 d33= 400pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
100	22.98	-200.73	188.01	4320.37	74.73	1717.40
300	16.84	-203.43	137.77	2320.09	54.77	922.27
500	15.30	-204.26	125.17	1915.15	49.76	761.30
800	13.77	-205.18	112.66	1551.27	44.78	616.65
1000	13.76	-205.19	112.57	1549.02	44.75	615.76

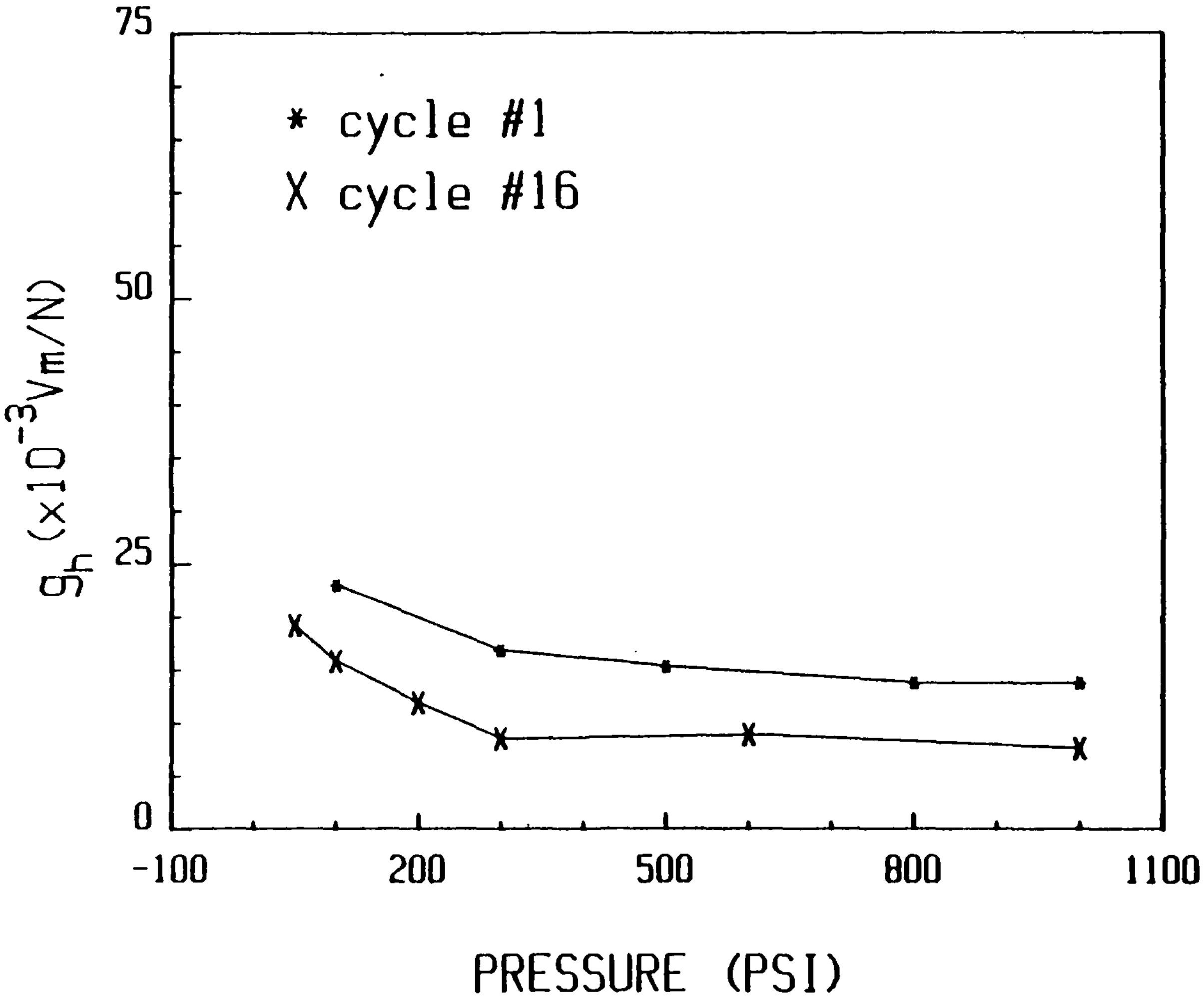
Cycle 16

C= 515pf KE= 908.84 KC= 361.28 d33= 400pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
50	19.18	-202.30	154.34	2960.22	61.35	1176.74
100	15.83	-203.97	127.38	2016.46	50.64	801.58
200	11.90	-206.45	95.76	1139.52	38.07	452.98
300	8.54	-209.33	68.72	586.87	27.32	233.29
600	8.90	-208.97	71.62	637.39	28.47	253.37
1000	7.58	-210.37	61.00	462.34	24.25	183.79

Flexane #60 foamed Matrix and #30 Jacket.
16, 3-1 Extruded Safari PZT elements.
Center hole filled with fiber frax.
Electrode Flexane #30 + 45% VME carbon fiber.

FLEX 23



* cycle #1
X cycle #16
75
50
25
0
-100
200
500
800
1100
g_h (x10^{-3}Vm/N)
PRESSURE (PSI)

FLEX 24

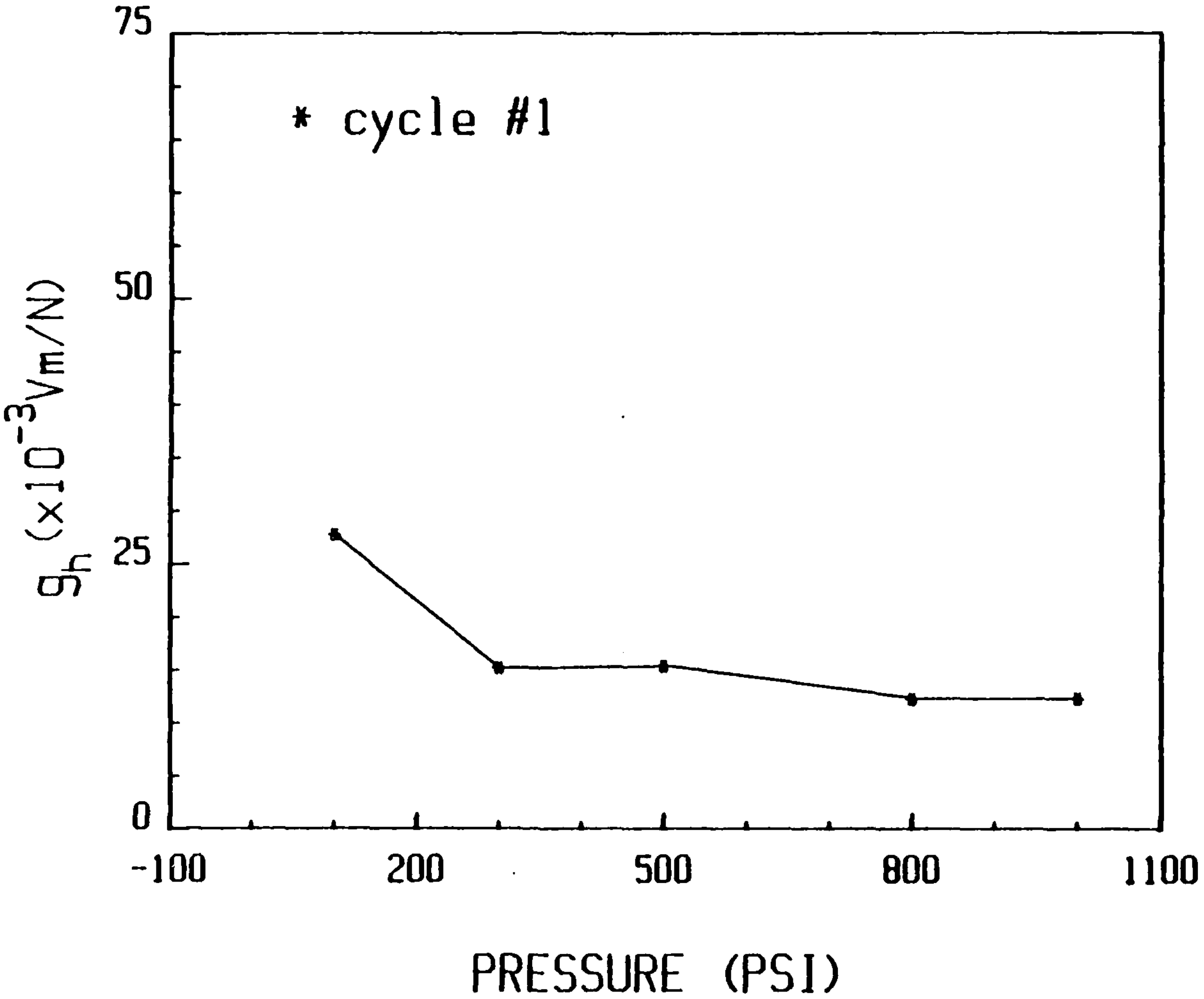
Cycle 01

C= 478.3pf KE= 843.9 KC= 335.46 d33= 380pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
100	27.79	-199.08	207.64	5770.42	82.54	2293.81
300	15.20	-204.32	113.57	1726.31	45.15	686.23
500	15.40	-204.21	115.07	1772.03	45.74	704.40
800	12.31	-206.15	91.78	1132.26	36.56	450.09
1000	12.31	-206.15	91.98	1132.26	36.56	450.09

Flexane #30 foamed Matrix and #30 Jacket.
16, 3-1 Extruded Safari PZT elements.
Center hole filled with fiber frax.
Electrode Flexane #30 + 45% VME carbon fiber.

FLEX 24



* cycle #1
75
50
25
0
g_h ($\times 10^{-3}$Vm/N)
-100
200
500
800
1100
PRESSURE (PSI)

Cycle 01

C= 540.82pf KE= 954.41 KC= 379.39 d33= 370pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
100	17.19	-203.25	145.26	2497.04	57.74	992.61
300	10.31	-207.69	87.12	378.24	34.63	357.06
500	10.31	-207.69	87.12	898.24	34.63	357.06
800	10.30	-207.70	87.04	896.50	34.60	356.37
1000	10.30	-207.70	87.04	896.50	34.60	356.37

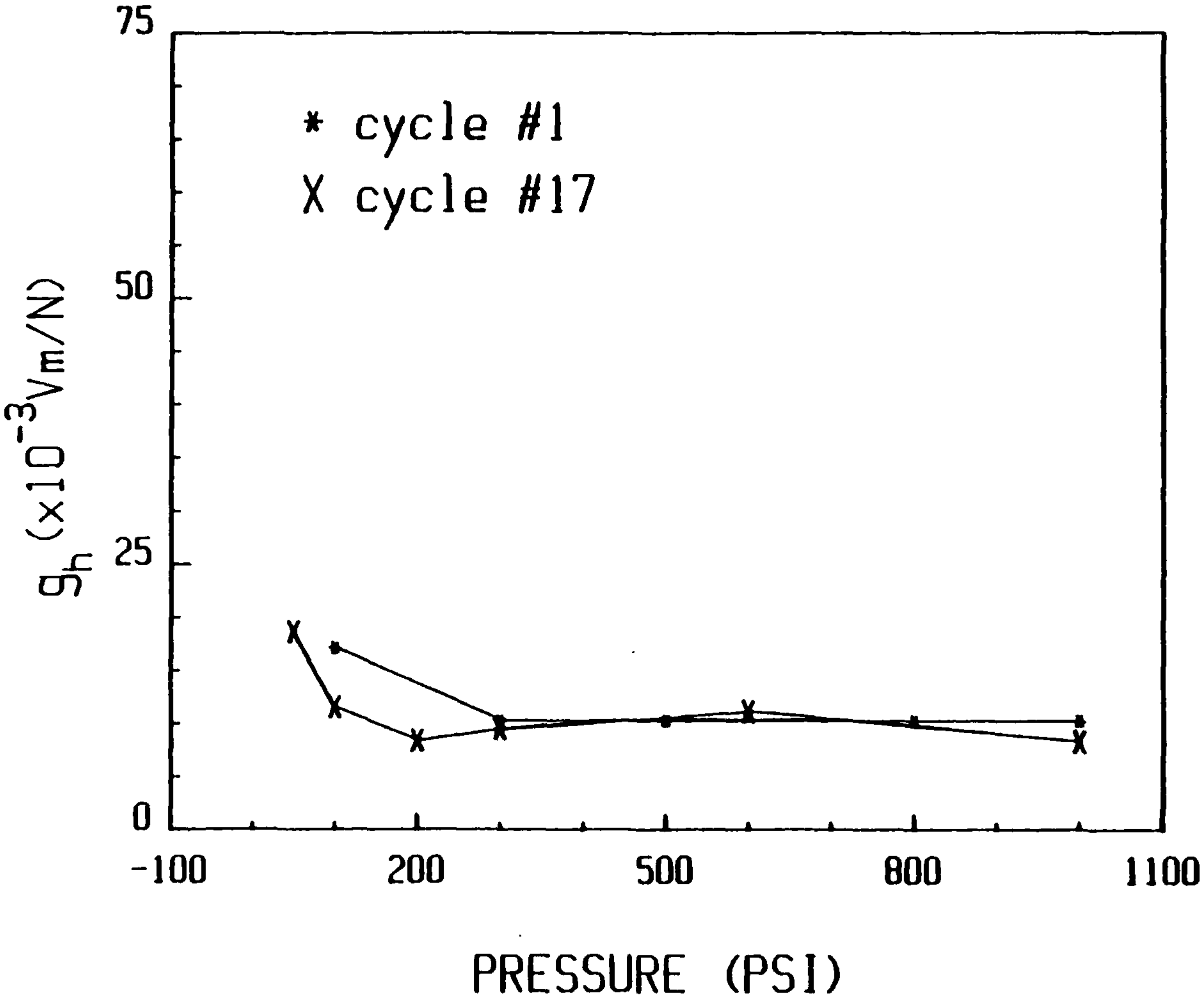
Cycle 17

C= 534.6pf KE= 943.43 KC= 375.03 d33= 370pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
50	18.68	-202.53	156.04	2914.76	62.03	1158.67
100	11.55	-206.71	96.48	1114.33	38.35	442.97
200	8.41	-209.46	70.25	590.80	27.93	234.85
300	9.51	-208.40	79.44	755.46	31.58	300.31
600	11.15	-207.01	93.14	1038.48	37.02	412.81
1000	8.30	-209.58	69.33	575.45	27.56	228.75

Flexane #60 unbonded Matrix and #30 Jacket.
16, 3-1 Extruded Safari PZT elements.
Center hole filled with wood.
Electrode Flexane #30 + 45% VME carbon fiber.

FLEX 25



* cycle #1
X cycle #17
75
50
25
0
-100
200
500
800
1100
g_h (x10^{-3}Vm/N)
PRESSURE (PSI)

Cycle 01

C= 470pf KE= 829.43 KC= 329.71 d33= 360pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
100	11.57	-206.69	84.97	983.07	33.78	390.79
300	13.89	-205.10	102.01	1416.85	40.55	563.22
500	13.89	-205.10	102.01	1416.85	40.55	563.22
800	12.34	-206.13	90.62	1118.28	36.02	444.53
1000	9.84	-208.10	72.26	711.07	28.73	282.66

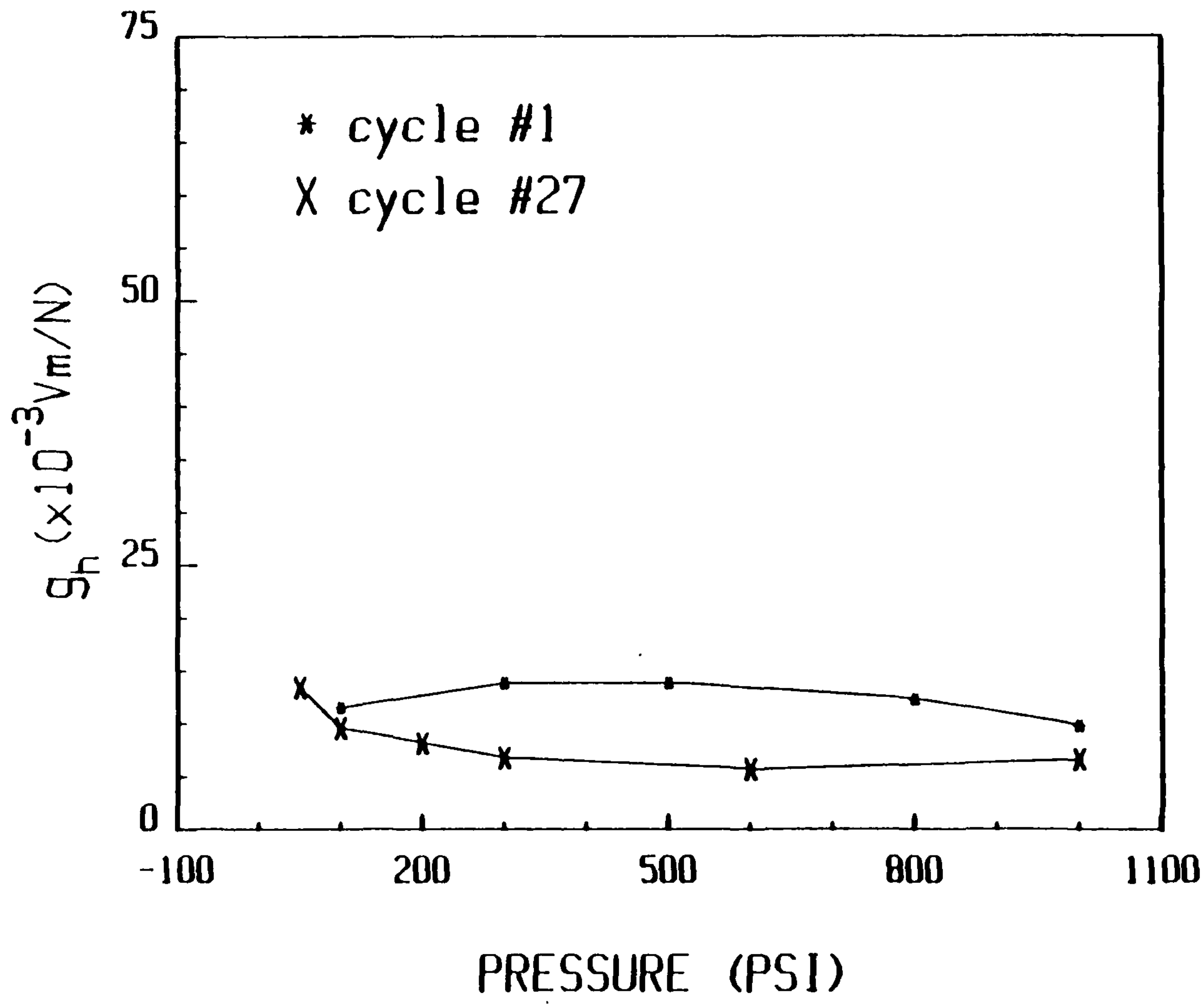
Cycle 27

C= 470pf KE= 829.43 KC= 329.71 d33= 360pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
50	13.44	-205.39	98.70	1326.53	39.23	527.32
100	9.58	-208.33	70.35	673.99	27.97	267.92
200	8.16	-209.72	59.93	488.99	23.82	194.38
300	6.79	-211.32	49.86	338.58	19.82	134.59
600	5.72	-212.81	42.01	240.28	16.70	95.51
1000	6.64	-211.52	48.76	323.78	19.38	128.71

Flexane #30 + 40% M.B. (micro ballons) Matrix and #30 Jacket.
16, 3-1 Extruded Safari PZT elements.
Center hole filled with fiber frax.
Electrode Flexane #30 + 45% VME carbon fiber.

FLEX 26



* cycle #1
X cycle #27
75
50
25
0
-100
200
500
800
1100
g_h (x10^{-3}Vm/N)
PRESSURE (PSI)

FLEX 27

Cycle 01

C= 422.06pf KE= 744.83 KC= 296.08 d33= 340pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
50	4.90	-214.15	32.31	158.34	12.85	62.94
100	29.11	-198.68	191.97	5588.32	76.31	2221.43
200	25.49	-199.83	168.10	4284.86	66.82	1703.29
300	13.62	-205.28	89.82	1223.35	35.70	486.30
400	6.46	-211.75	42.60	275.21	16.93	109.40
500	14.02	-205.02	92.46	1296.26	36.75	515.28
600	14.01	-205.03	92.39	1294.41	36.73	514.55
700	11.52	-206.73	75.97	875.19	30.20	347.90
800	11.02	-207.12	72.67	800.87	28.89	318.36
1000	10.27	-207.73	67.73	695.56	26.92	276.50

Cycle 03

C= 422.06pf KE= 744.83 KC= 296.08 d33= 340pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
100	13.17	-205.57	86.85	1143.85	34.53	454.69
200	9.54	-208.37	62.91	600.20	25.01	238.59
300	8.05	-209.84	53.09	427.35	21.10	169.88
400	6.82	-211.28	44.78	306.74	17.88	121.93
500	8.81	-209.06	58.10	511.86	23.10	203.47
600	6.61	-211.55	43.59	288.14	17.33	114.54
700	6.22	-212.08	41.02	255.14	16.31	101.42
800	6.54	-211.65	43.13	282.07	17.14	112.13
1000	7.01	-211.04	46.23	324.07	18.38	128.82

FLEX 27

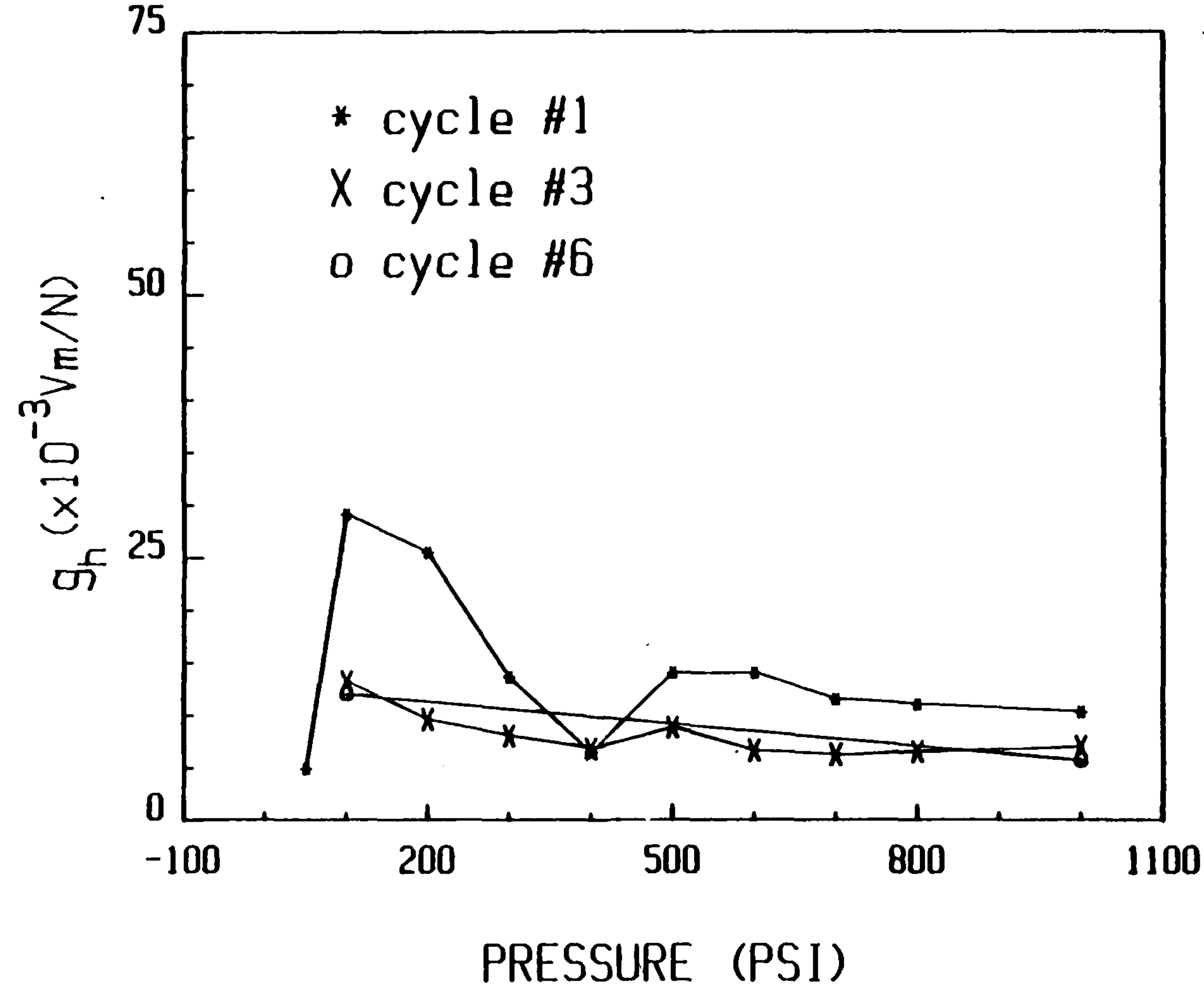
Cycle 36

C= 422.06pf KE= 744.83 KC= 296.08 d33= 340pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
100	11.92	-206.43	78.61	937.02	31.25	372.48
1000	5.60	-213.00	36.93	206.81	14.68	82.21

Corepreen Matrix and Flexane #30 Jacket.
16, 3-1 Extruded Safari PZT elements.
Center hole filled with fiber frax.
Electrode Flexane #30 + 45% VME carbon fiber.

FLEX 27



* cycle #1
X cycle #3
o cycle #6
75
50
25
0
g_h ($\times 10^{-3}$Vm/N)
-100
200
500
800
1100
PRESSURE (PSI)

FLEX 28

Cycle 01

C= 480.86pf KE= 848.59 KC= 337.33 d33= 360pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
25	15.51	-204.15	116.53	1807.43	46.32	718.49
100	13.41	-205.41	100.75	1351.12	40.05	537.10
200	11.79	-206.53	88.58	1044.40	35.21	415.17
300	12.25	-206.20	92.04	1127.48	36.59	448.19
400	13.88	-205.11	104.29	1447.49	41.46	575.40
500	11.01	-207.12	82.72	910.78	32.88	362.05
600	8.93	-208.94	67.09	599.16	26.67	238.18
700	9.85	-208.09	74.01	728.97	29.42	289.78
800	10.29	-207.71	77.31	795.55	30.73	316.25
1000	9.91	-208.04	74.46	737.88	29.60	293.32

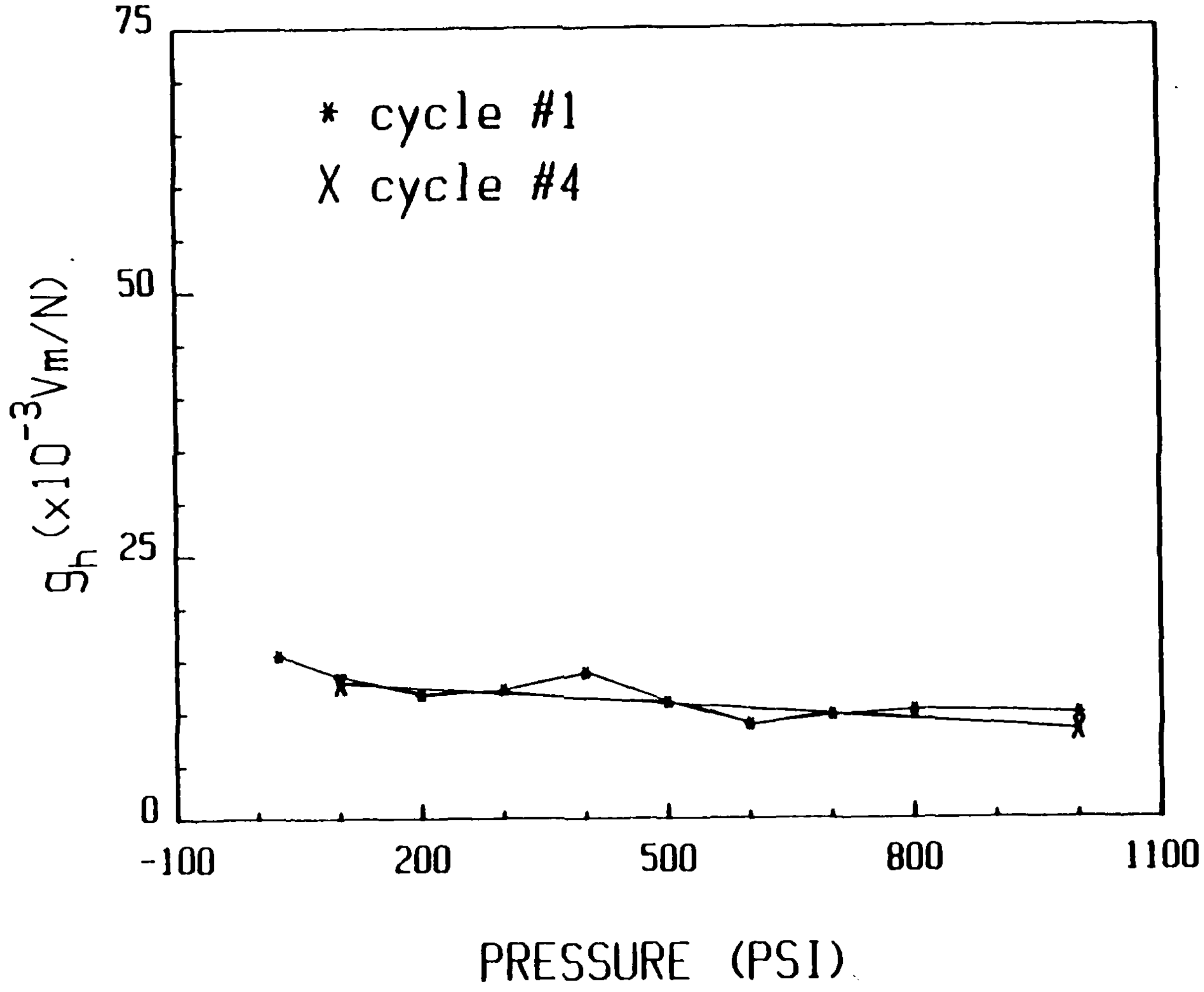
Cycle 04

C= 480.86pf KE= 848.59 KC= 337.33 d33= 360pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
100	12.83	-205.79	96.40	1236.78	38.32	491.64
1000	8.32	-209.56	62.51	520.10	24.85	206.75

Flexane #60 Matrix and #30 Jacket.
16, 3-1 Extruded Safari PZT elements.
Center hole filled with fiber frax.
Electrode bonded silver wire.

FLEX 28



* cycle #1
X cycle #4
75
50
25
0
g_h $(\times 10^{-3} Vm/N)$
-100
200
500
800
1100
PRESSURE (PSI)

Cycle 01

C= 358.64pf KE= 632.91 KC= 251.59 d33= 360pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
35	37.76	-196.42	211.60	7989.98	84.11	3176.12
100	40.89	-195.73	229.14	9369.48	91.09	3724.49
200	18.78	-202.48	105.24	1976.39	41.83	785.64
300	14.54	-204.71	81.48	1184.71	32.39	470.94
400	12.95	-205.71	72.57	939.77	28.85	373.57
500	11.85	-206.48	66.40	786.70	26.40	312.80
600	10.51	-207.53	58.90	618.99	23.41	246.06
700	13.26	-205.51	74.31	985.30	29.54	391.67
800	10.17	-207.81	56.99	579.59	22.65	230.40
1000	8.29	-209.59	46.46	385.12	18.47	153.09

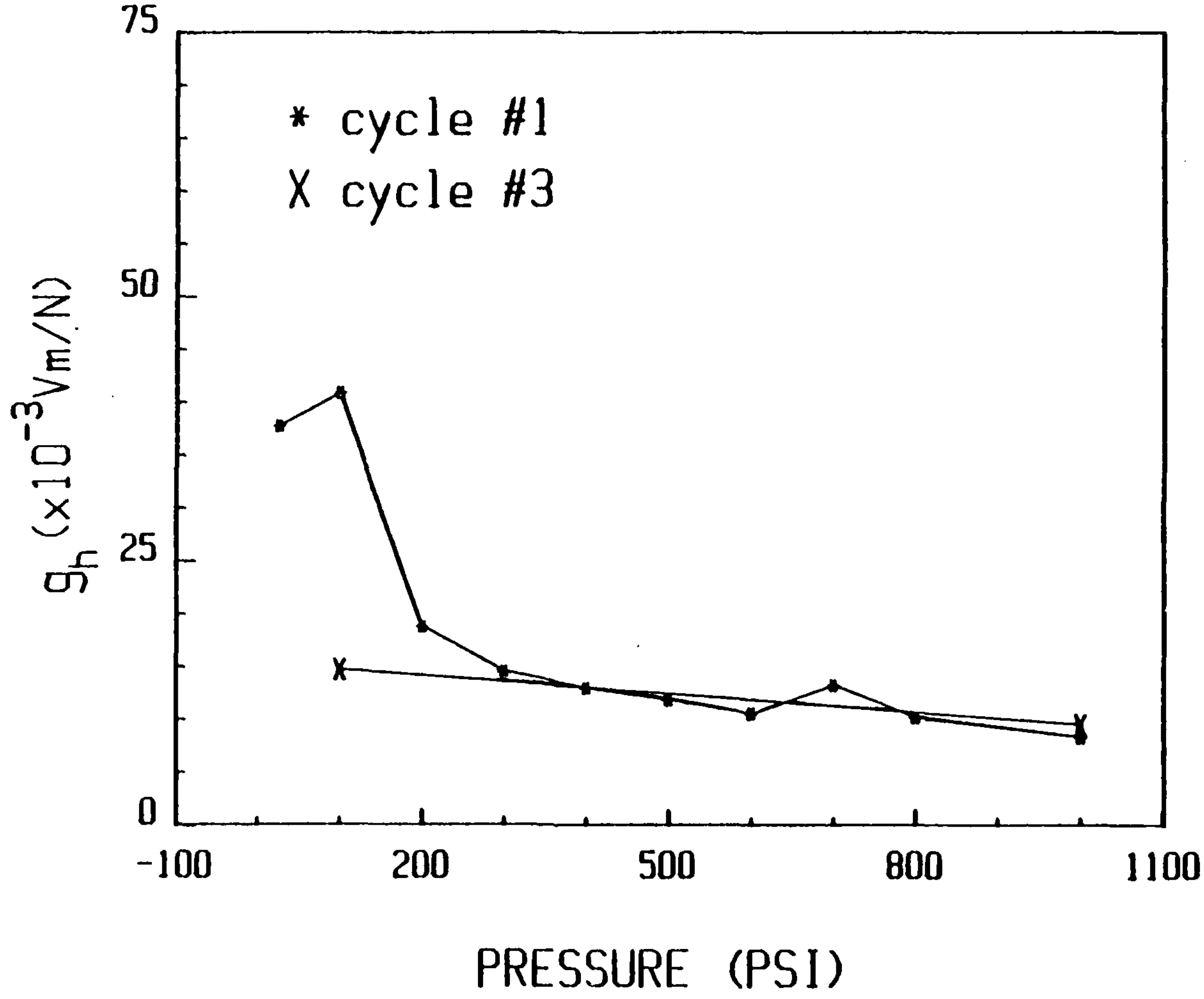
Cycle 03

C= 358.64pf KE= 632.91 KC= 251.59 d33= 360pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
100	14.70	-204.61	82.38	1210.92	32.75	481.36
1000	9.47	-203.43	53.07	502.55	21.10	[illegible]

Flexane #30 + 55% M.B. Matrix and #30 Jacket.
16, 3-1 Extruded Safari PZT elements.
Center hole filled with fiber frax.
Electrode Flexane #30 + 45% VME carbon fiber.

FLEX 29



* cycle #1
X cycle #3
75
50
25
0
-100
200
500
800
1100
g_h ($\times 10^{-3}$ Vm/N)
PRESSURE (PSI)

FLEX 30

Cycle 01

C= 504.52pf   KE= 890.35   KC= 353.93   d33= 380pC/N   ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
25	16.38	-203.67	129.13	2115.09	51.33	840.78
100	17.85	-202.93	140.71	2511.75	55.94	998.47
200	21.48	-201.32	169.33	3637.21	67.31	1445.86
300	19.46	-202.18	153.41	2985.29	60.98	1186.70
400	14.57	-204.69	114.86	1673.48	45.66	665.24
500	11.19	-206.98	88.21	987.10	35.07	392.39
600	11.32	-206.88	89.24	1010.17	35.47	401.56
700	12.27	-206.18	96.73	1186.83	38.45	471.79
800	9.82	-208.12	77.41	760.19	30.77	302.19
1000	9.21	-208.67	72.60	668.68	28.86	265.81

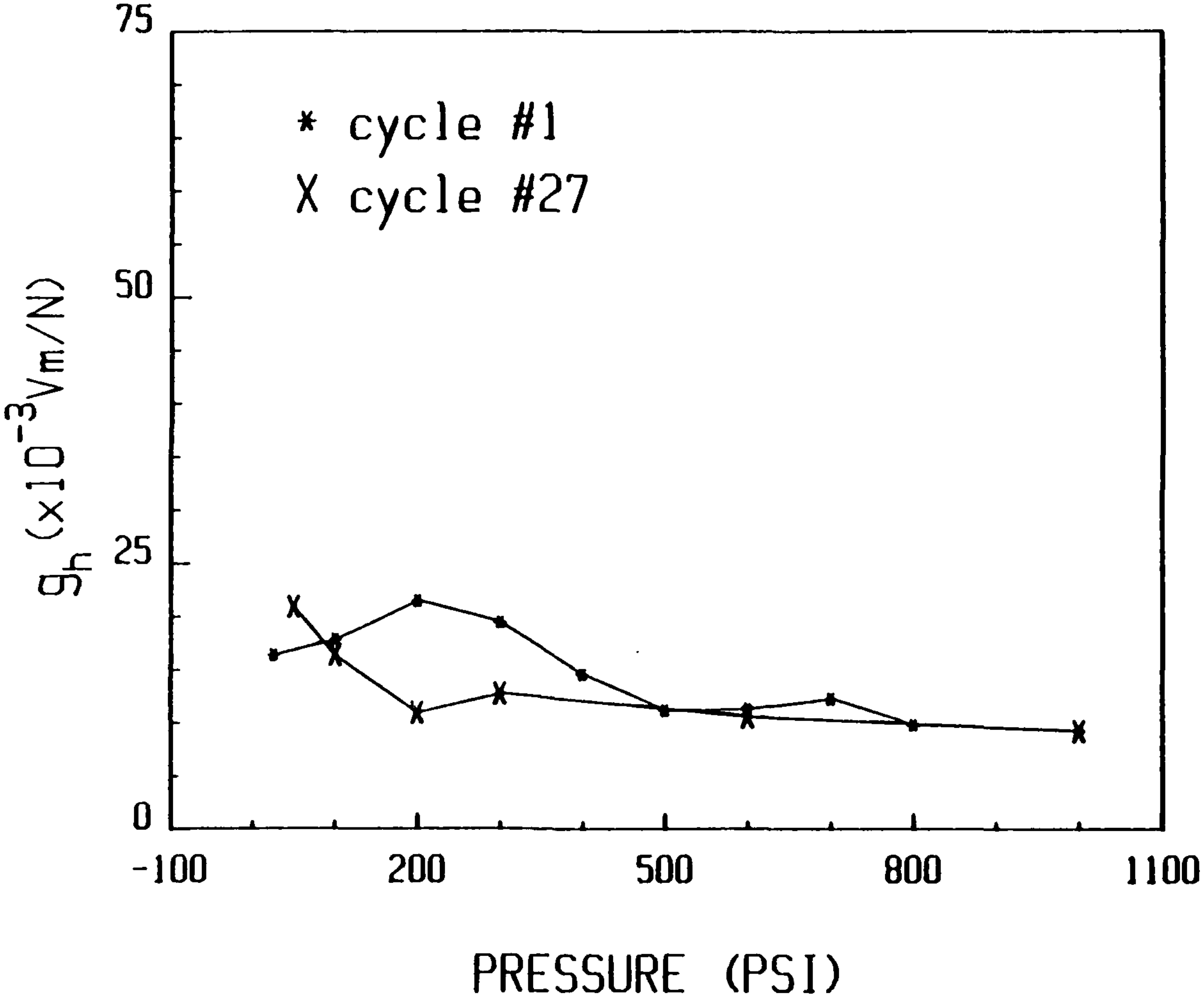
Cycle 27

C= 504.52pf   KE= 890.35   KC= 353.93   d33= 380pC/N   ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
50	20.39	-201.56	164.68	3440.15	65.46	1367.52
100	16.36	-203.68	128.97	2109.92	51.27	838.73
200	10.96	-207.16	86.40	946.94	34.35	376.42
300	12.74	-205.86	100.43	1279.50	39.92	508.62
600	10.53	-207.51	83.01	874.09	33.00	347.47
1000	9.22	-208.66	72.68	670.13	28.89	266.39

Flexane #30 + 40% P.M.M. (Poly methyl methacrylate) Matrix and #30 Jacket.
16, 3-1 Extruded Safari PZT elements.
Center hole filled with fiber frax.
Electrode Flexane #30 + 45% VME carbon fiber.

FLEX 30



* cycle #1
X cycle #27
75
50
25
0
g_h (x10^{-3}Vm/N)
-100
200
500
800
1100
PRESSURE (PSI)

Cycle 01

C= 368.6pf KE= 756.93 KC= 258.58 d33= 424pC/N ELMA= 2.2cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
0	26.30	-199.56	176.26	4635.61	60.21	1583.60
100	33.33	-197.50	223.37	7445.02	76.31	2543.34
300	25.53	-199.82	171.10	4368.14	58.45	1492.23
600	23.33	-200.60	156.35	3647.73	53.41	1246.13
1000.	19.21	-202.29	128.74	2473.15	43.98	844.87

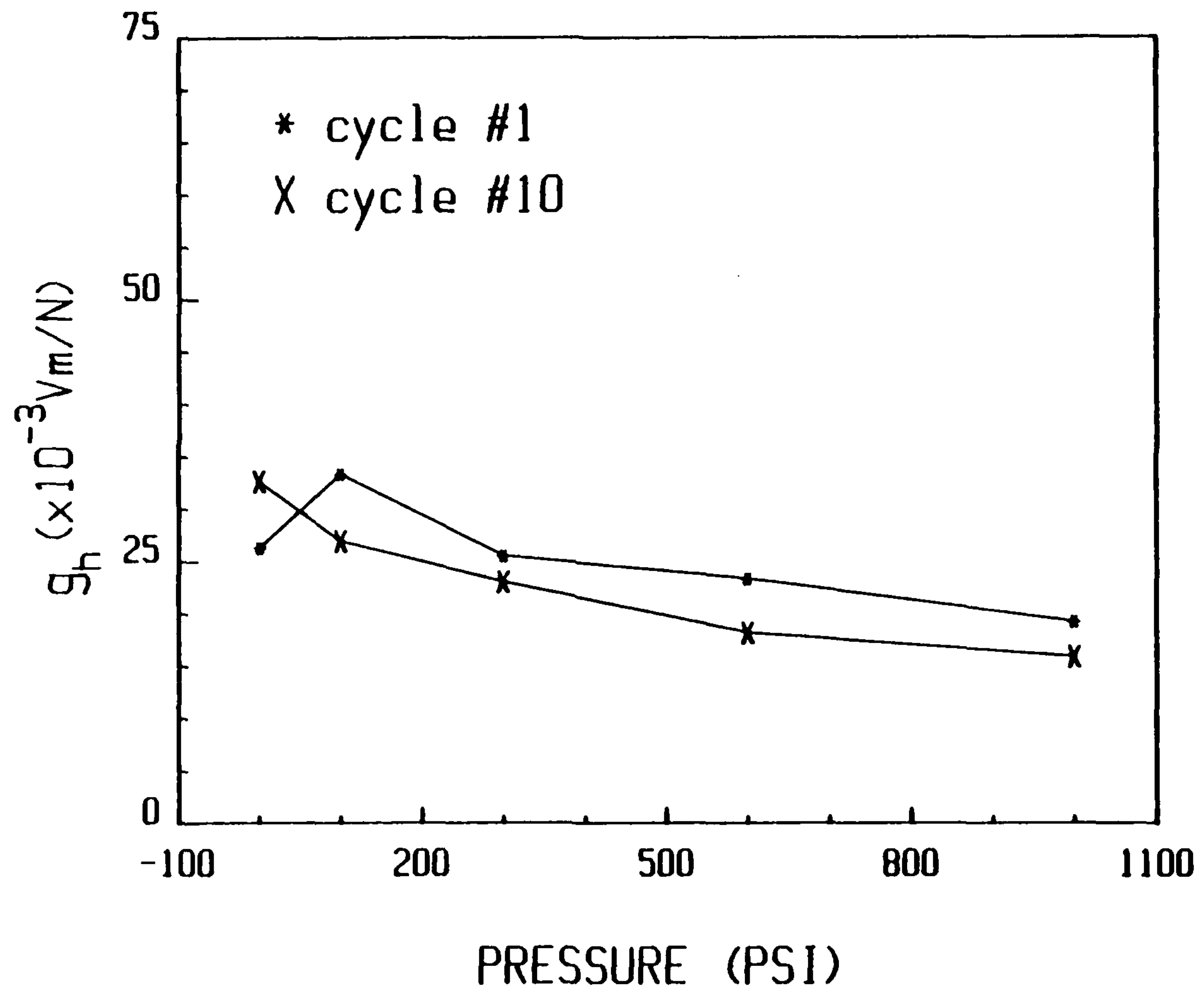
Cycle 10

C= 368.6pf KE= 756.93 KC= 258.58 d33= 424pC/N ELMA= 2.2cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
0	32.61	-197.69	218.55	7126.84	74.66	2434.65
100	26.93	-199.35	180.48	4860.35	61.66	1660.38
300	23.02	-200.72	154.28	3551.45	52.70	1213.24
600	18.16	-202.78	121.71	2210.18	41.58	755.03
1000	15.35	-203.96	106.22	1683.66	36.29	575.17

Flexane #30 + 40% P.M.M.M Matrix and #30 Jacket.
4, 3-1 Machined Safari PZT Bars.
Center hole filled with Spurrs Epoxy.
Electrode Flexane #30 + 45% VME carbon fiber.

FLEX 31



* cycle #1
X cycle #10
75
50
25
0
g_h $(\times 10^{-3} Vm/N)$
-100
200
500
800
1100
PRESSURE (PSI)

Cycle 01

C= 400.9pf KE= 767.44 KC= 281.24 d33= 383pC/N ELMA= 2.36cm2 COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
0	54.70	-193.20	371.68	20330.99	136.21	7450.60
100	51.00	-193.81	346.54	17673.57	127.00	6476.75
300	31.30	-198.05	212.68	6656.91	77.94	2439.53
600	36.30	-196.76	246.66	8953.59	90.39	3281.18
1000	31.30	-198.05	212.68	6656.91	77.94	2439.53

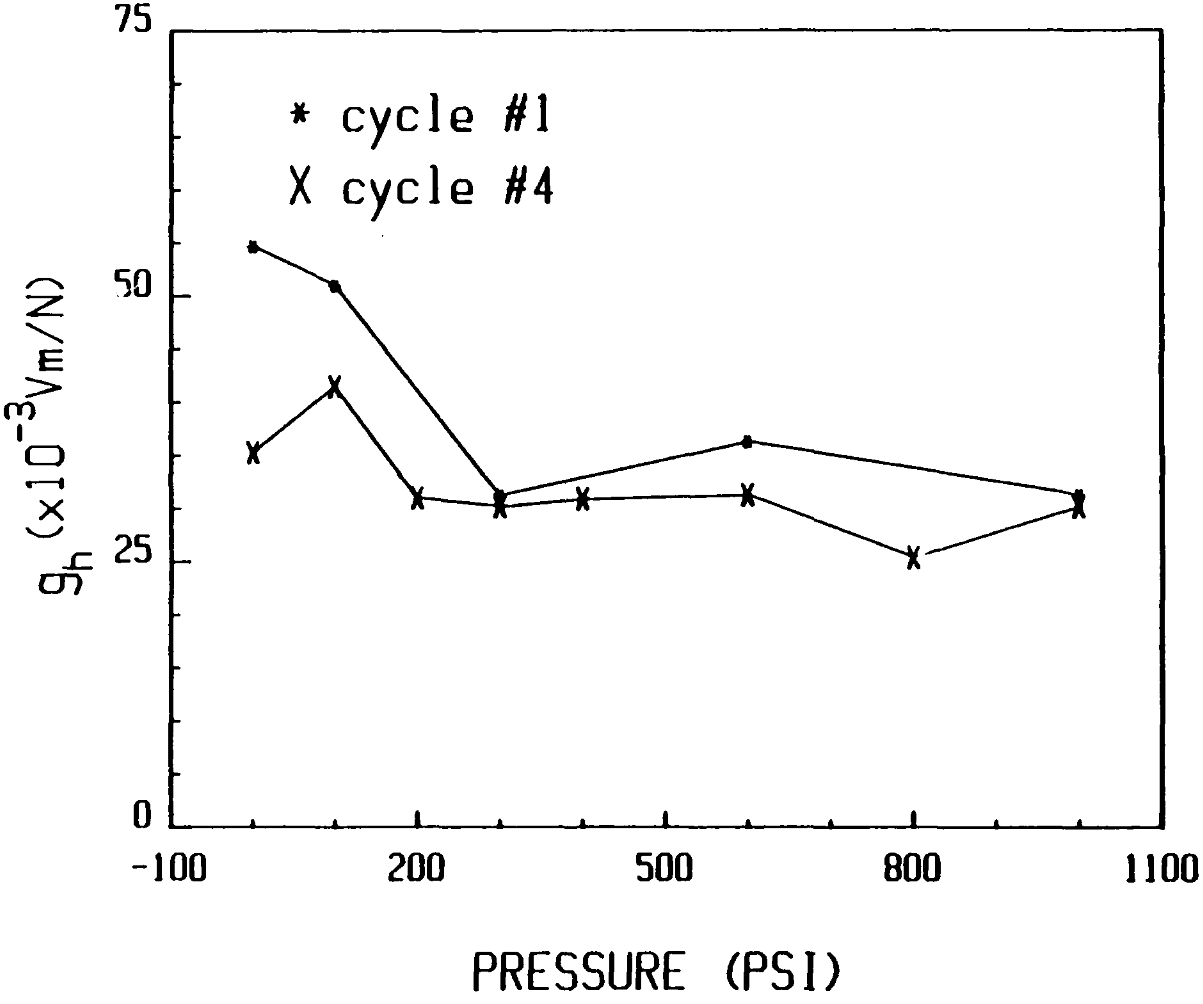
Cycle 04

C= 400.9pf KE= 767.44 KC= 281.24 d33= 383pC/N ELMA= 2.36cm2 COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
0	35.30	-197.00	239.86	8467.07	87.90	3102.89
100	41.50	-195.60	281.99	11702.54	103.34	4288.57
200	31.00	-198.13	210.64	6529.91	77.19	2392.99
300	30.20	-198.36	205.21	6197.23	75.20	2271.07
400	30.90	-198.16	209.96	6487.85	76.94	2377.57
600	31.30	-198.05	212.68	6656.91	77.94	2439.53
800	25.40	-199.86	172.59	4383.81	63.25	1606.51
1000	30.20	-198.36	205.21	6197.23	75.20	2271.07

Flexane #30 + 40% P.M.M. Matrix and #30 Jacket.
16, 3-1 Machined Safari PZT elements.
Center hole filled with Spurrs Epoxy.
Electrode Flexane #30 + 45% VME carbon fiber.

FLEX 32



* cycle #1
X cycle #4
g_h ($\times 10^{-3}$Vm/N)
75
50
25
0
-100
200
500
800
1100
PRESSURE (PSI)

Cycle 01

C= 480.13pf KE= 847.3 KC= 336.82 d33= 342pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
0	25.03	-199.99	187.77	4700.01	74.64	1868.35
100	17.71	-202.99	132.86	2352.96	52.31	935.35
300	10.25	-207.74	76.90	788.18	30.57	313.32
600	10.10	-207.87	75.77	765.28	30.12	304.21
1000	9.24	-208.65	69.32	640.50	27.56	254.61

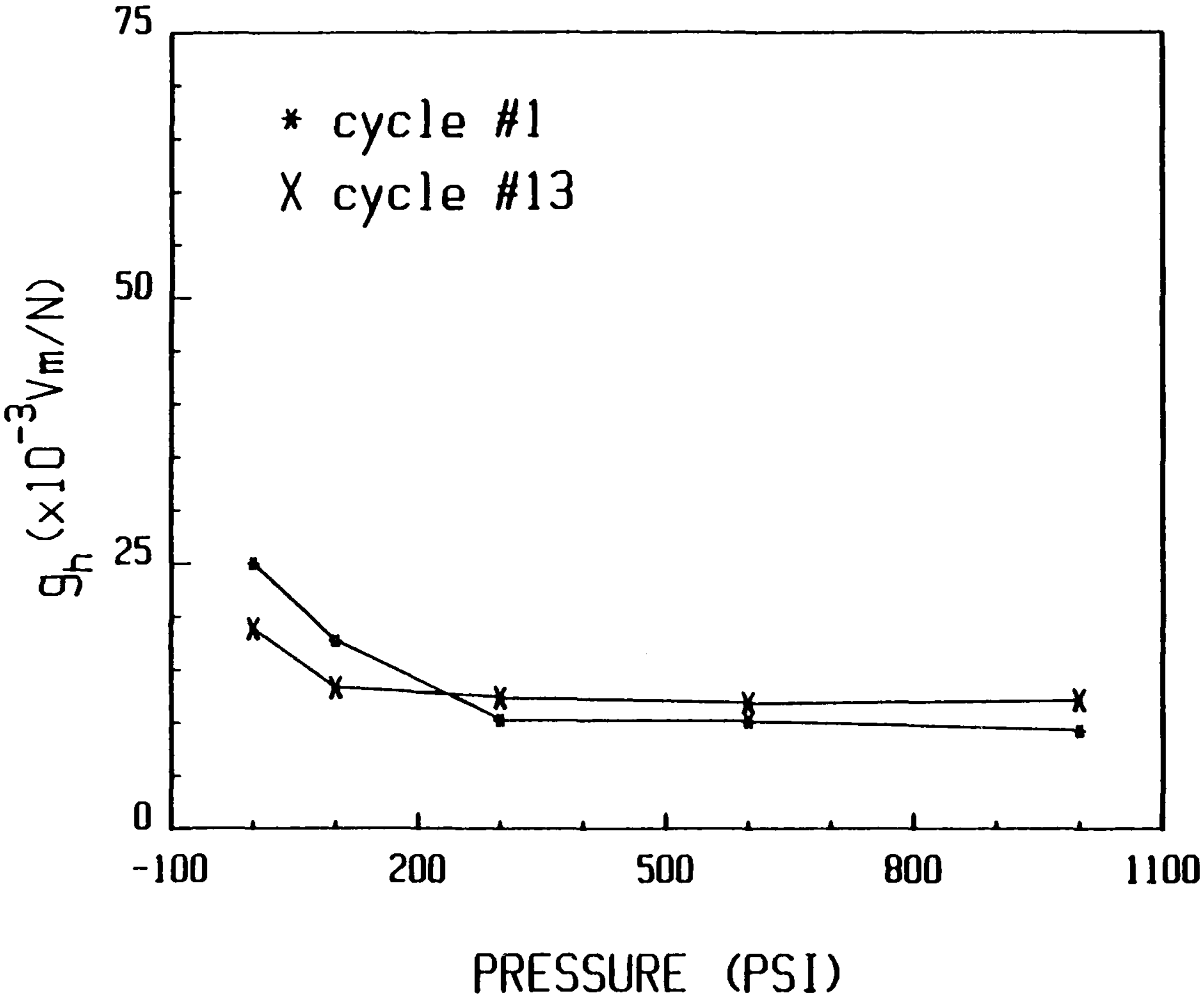
Cycle 13

C= 480.13pf KE= 847.3 KC= 336.82 d33= 342pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
0	18.87	-202.44	141.56	2671.29	56.27	1061.87
100	13.30	-205.48	99.78	1327.03	39.66	527.52
300	12.33	-206.14	92.50	1140.52	36.77	453.38
600	11.83	-206.50	88.75	1049.70	35.28	417.36
1000	12.12	-206.29	90.92	1102.00	36.14	438.07

Flexane #30 + 40% M.B. Matrix and #30 Jacket.
16, 3-1 Extruded Safari PZT elements.
Center hole filled with Tra-bond 2113 epoxy.
Electrode Flexane #30 + 45% VME carbon fiber.

FLEX 33



* cycle #1
X cycle #13
75
50
25
0
g_h ($\times 10^{-3}$Vm/N)
-100
200
500
800
1100
PRESSURE (PSI)

Cycle 01

C= 396.6pf KE= 699.9 KC= 278.22 d33= 276pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
0	29.21	-198.65	181.01	5287.36	71.95	2101.80
100	21.97	-201.12	136.15	2991.13	54.12	1189.02
300	11.74	-206.57	72.75	854.11	28.92	339.52
600	12.99	-205.69	80.50	1045.67	32.00	415.67
1000	11.59	-206.68	71.82	832.42	28.55	330.90

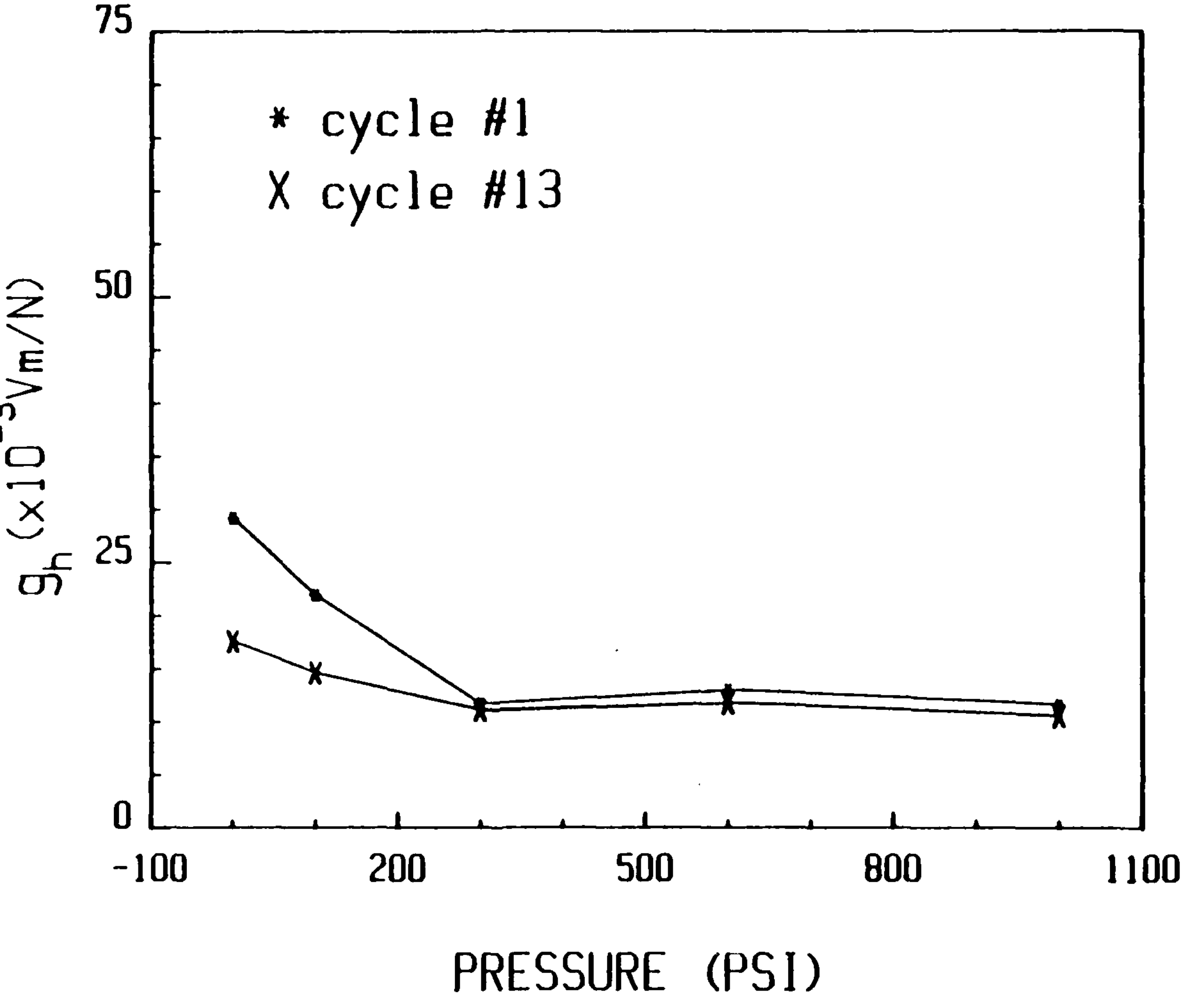
Cycle 13

C= 396.6pf KE= 699.9 KC= 278.22 d33= 276pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
0	17.56	-203.07	108.82	1910.84	43.26	759.59
100	14.61	-204.67	90.54	1322.74	35.99	525.81
300	11.08	-207.07	68.66	760.77	27.29	302.42
600	11.75	-206.56	72.81	855.56	28.94	340.10
1000	10.50	-207.54	65.07	683.21	25.87	271.59

Flexane #60 foamed Matrix and #30 Jacket.
16, 3-1 Extruded Safari PZT elements.
Center hole filled with Tra-bond 2113 epoxy.
Electrode Flexane #30 + 45% VME carbon fiber.

FLEX 34


* cycle #1
X cycle #13
75
50
25
0
-100
200
500
800
1100
g_h (x10^{-3}Vm/N)
PRESSURE (PSI)

FLEX 35

Cycle 01

C= 553.8pf KE= 977.31 KC= 388.5 d33= 313pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	21.59	-201.27	186.82	4033.45	74.26	1603.38
100	20.34	-201.79	176.00	3579.92	67.77	1423.09
300	19.15	-202.32	165.71	3173.29	65.87	1261.44
500	16.58	-203.57	143.47	2378.71	57.03	945.58
900	16.41	-203.66	142.00	2330.18	56.45	926.39
1000	14.96	-204.46	129.45	1936.58	51.46	769.83

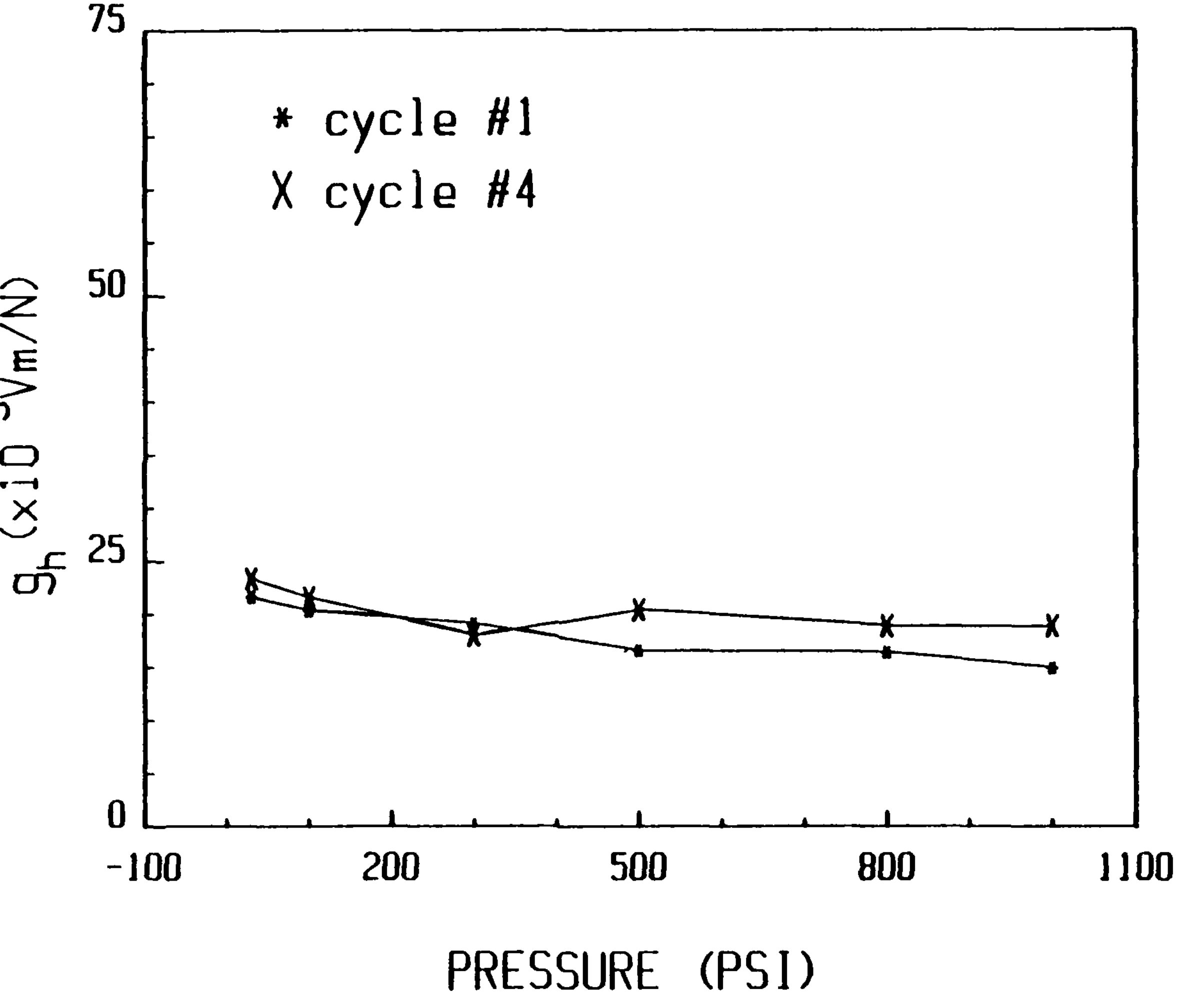
Cycle 04

C= 553.8pf KE= 977.31 KC= 388.5 d33= 313pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	23.35	-200.59	202.05	4717.87	80.32	1875.44
100	21.58	-201.28	136.73	4029.72	74.23	1601.89
300	18.03	-202.84	156.02	2812.96	62.02	1118.21
500	20.43	-201.75	176.78	3611.67	70.27	1435.71
300	18.70	-202.43	163.54	3090.97	65.01	1223.72
1000	13.90	-202.43	163.54	3090.97	65.01	1228.72

Flexane #60 Matrix and #30 Jacket.
16, 3-1 Machined Safari PZT elements.
Center hole filled with Tra-bond 2113 epoxy.
Electrode Flexane #30 + 45% VME carbon fiber.

FLEX 35



75
50
25
0
-100
200
500
800
1100
* cycle #1
X cycle #4
g_h (x10^{-3}Vm/N)
PRESSURE (PSI)

Cycle 01

C= 544.6pf KE= 961.08 KC= 382.04 d33= 365pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	14.28	-204.86	121.51	1735.22	48.30	689.77
100	12.26	-206.19	104.33	1277.03	41.47	508.43
300	9.81	-208.13	83.48	818.91	33.18	325.53
500	9.86	-208.08	83.90	827.28	33.35	328.85
300	9.81	-208.13	83.48	818.91	33.18	325.53
1000	11.66	-206.62	99.22	1156.90	39.44	457.88

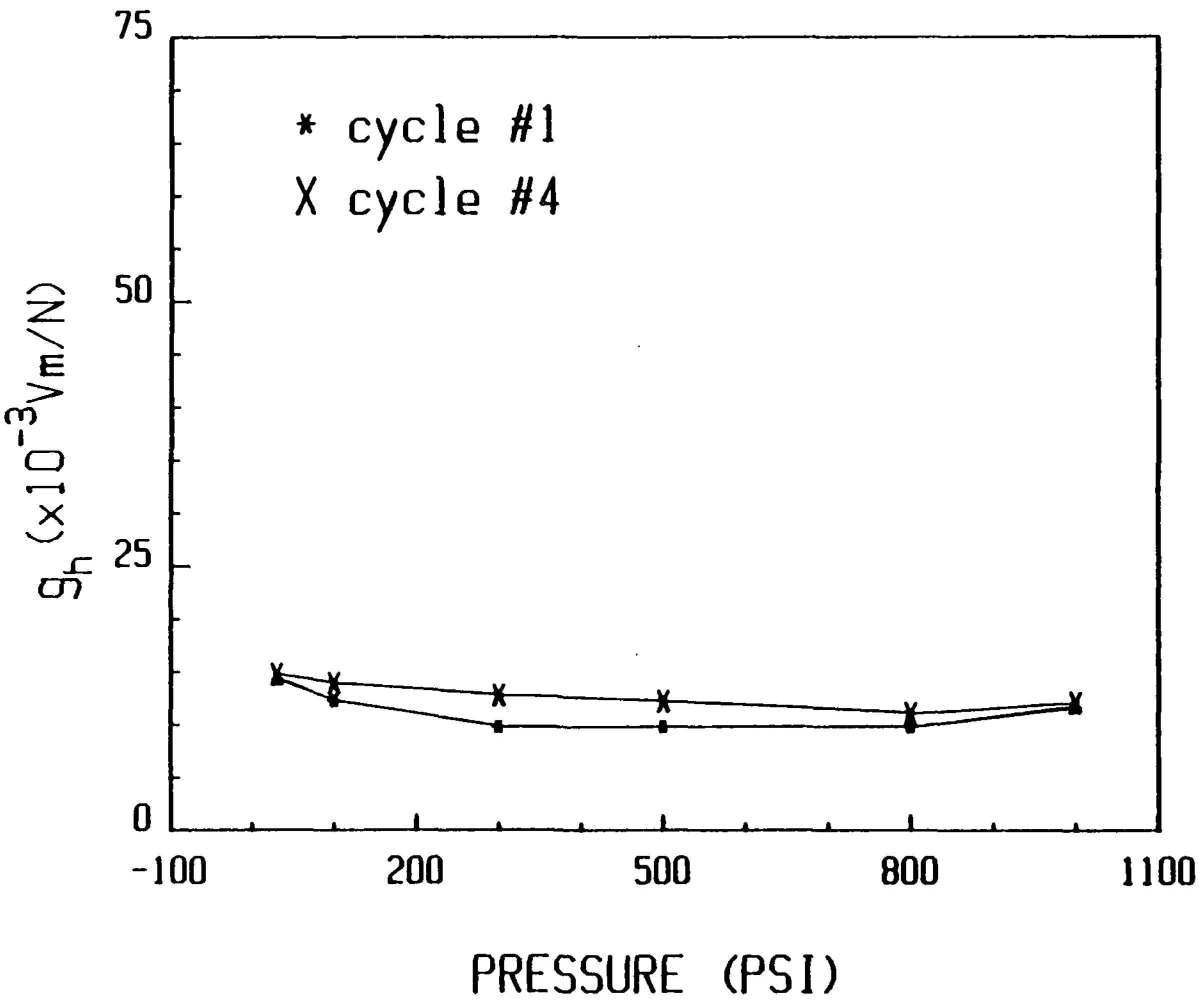
Cycle 04

C= 544.6pf KE= 961.08 KC= 382.04 d33= 365pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	14.74	-204.57	125.43	1848.82	49.86	734.93
100	13.91	-205.09	118.37	1646.47	47.05	654.49
300	12.76	-205.84	108.58	1385.48	43.16	550.74
500	12.21	-206.22	103.90	1268.62	41.30	504.29
800	11.07	-207.08	94.20	1042.78	37.45	414.52
1000	12.07	-206.32	102.71	1239.69	40.83	492.79

Flexane #30 Matrix and #30 Jacket.
16, 3-1 Machined Safari PZT elements.
Center hole filled with Tra-bond 2113 epoxy.
Electrode Flexane #30 + 45% VME carbon fiber.

FLEX 36



75
50
25
0
g_h ($\times 10^{-3}$ Vm/N)
* cycle #1
X cycle #4
-100
200
500
800
1100
PRESSURE (PSI)

FLEX 37

Cycle 01

C= 533.5pf KE= 941.49 KC= 374.26 d33= 365pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	29.29	-198.62	244.16	7151.45	97.06	2842.84
100	23.21	-200.65	193.48	4490.61	76.91	1785.10
300	17.32	-203.17	144.38	2500.64	57.39	994.05
500	15.03	-204.42	125.29	1883.10	49.80	748.57
800	17.38	-203.16	144.88	2517.99	57.59	1000.95
1000	14.96	-204.40	124.71	1865.60	49.57	741.61

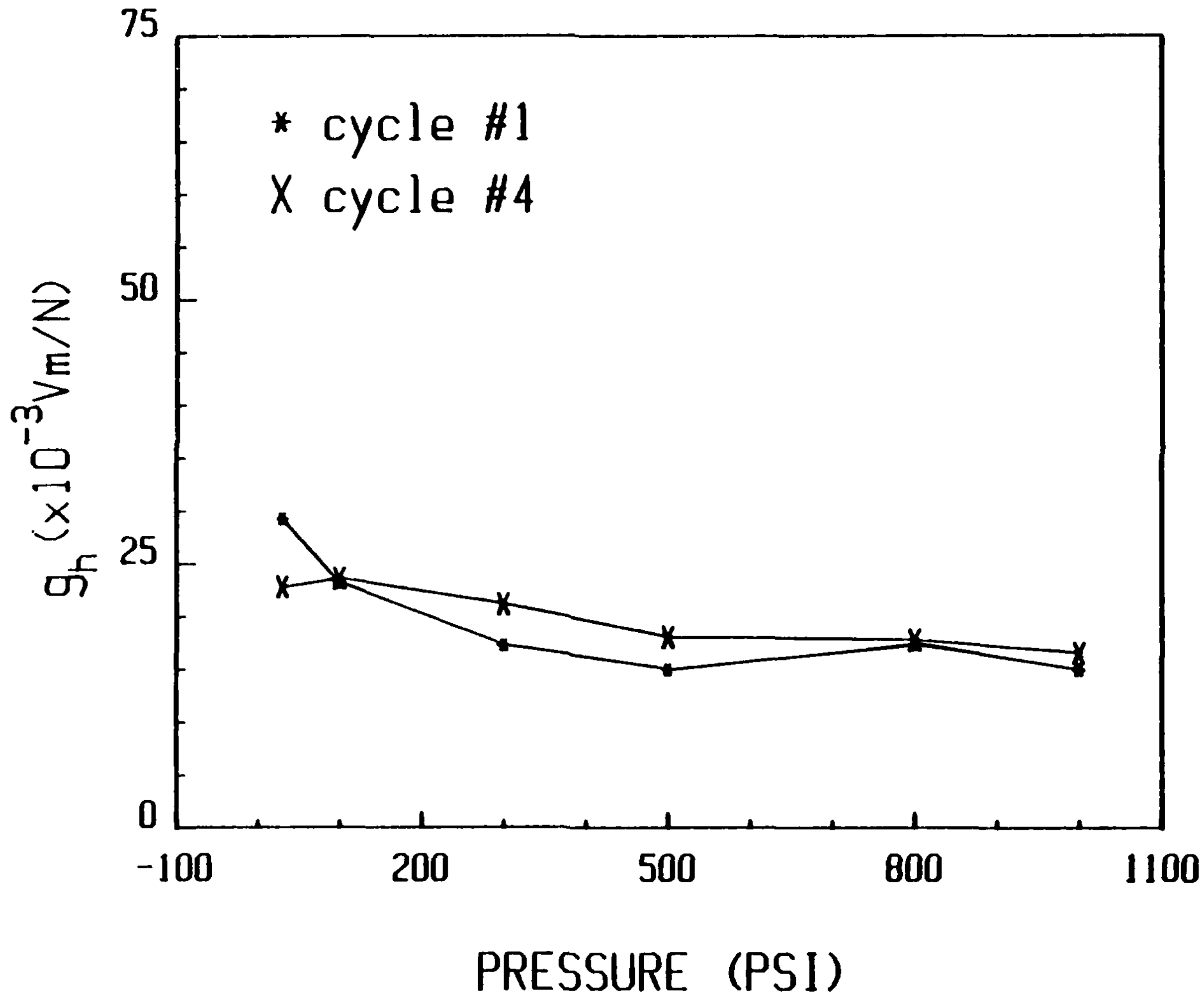
Cycle 04

C= 533.5pf KE= 941.49 KC= 374.26 d33= 365pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	22.82	-200.79	190.23	4340.97	75.62	1725.62
100	23.66	-200.48	197.23	4666.43	78.40	1854.99
300	21.21	-201.43	176.81	3750.05	70.28	1490.71
500	18.09	-202.81	150.80	2727.72	59.94	1084.40
800	17.80	-202.95	148.38	2641.16	58.98	1049.91
1000	16.56	-203.58	138.04	2286.00	54.87	908.73

Flexane #30 + 35% P.M.M. Matrix and #30 Jacket.
16, 3-1 Machined Safari PZT elements.
Center hole filled with Tra-bond 2113 epoxy.
Electrode Flexane #30 + 45% VME carbon fiber.

FLEX 37



75
50
25
0
g_h ($\times 10^{-3}$Vm/N)
* cycle #1
X cycle #4
-100
200
500
800
1100
PRESSURE (PSI)

FLEX 38

Cycle 01

C= 538.2pf KE= 949.78 KC= 377.55 d33= 313pC/N ELMA= 2.56cm2 COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	25.47	-199.84	214.19	5455.32	85.14	2168.56
100	22.55	-200.90	189.63	4276.18	75.38	1699.84
300	25.78	-199.73	216.79	5588.93	86.18	2221.67
500	16.57	-203.57	139.34	2308.91	55.39	917.82
800	19.16	-202.31	161.12	3087.12	64.05	1227.17
1000	15.18	-204.33	127.65	1937.79	50.74	770.30

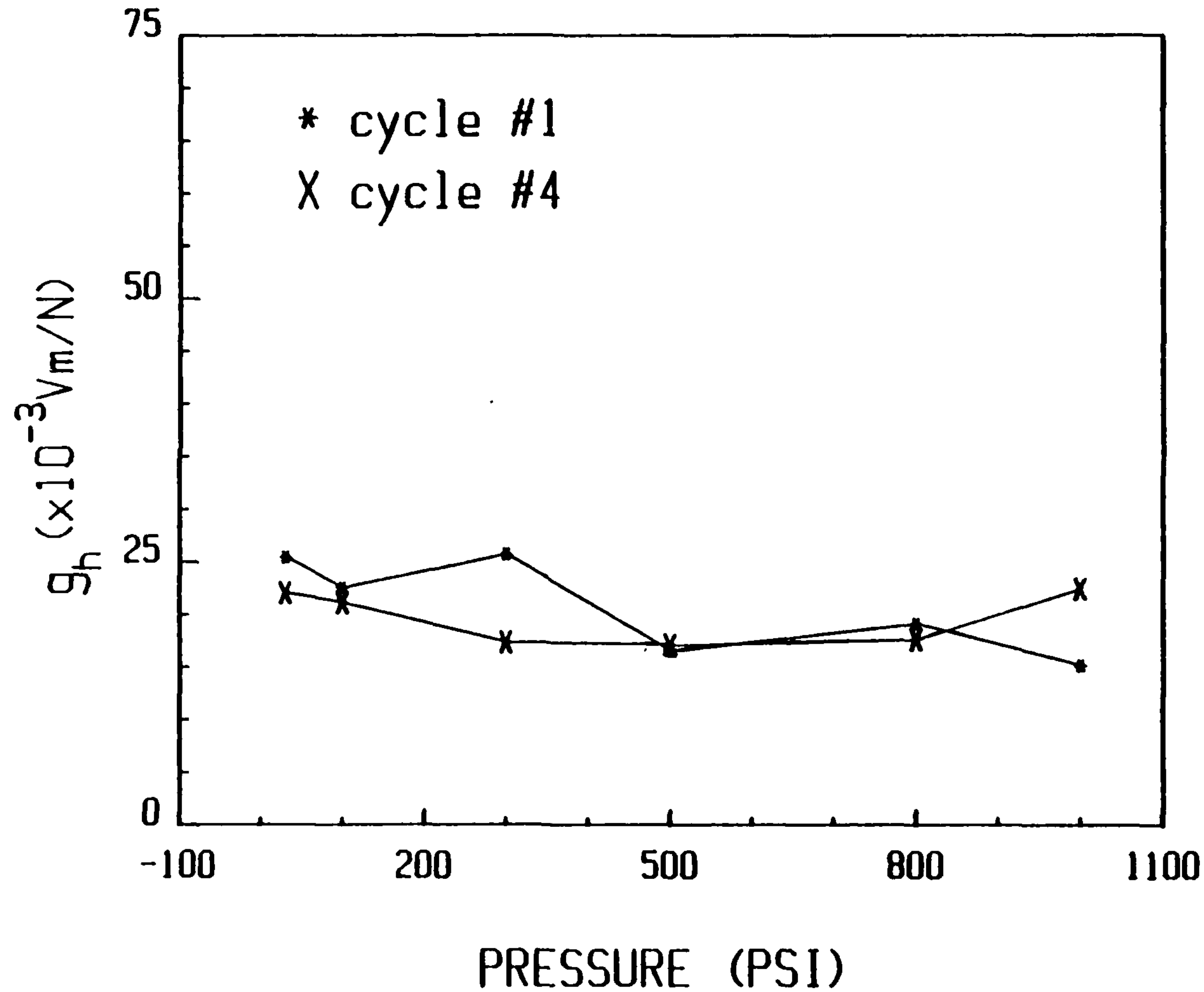
Cycle 04

C= 538.2pf KE= 949.78 KC= 377.55 d33= 313pC/N ELMA= 2.56cm2 COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	22.02	-201.10	185.17	4077.53	73.61	1620.87
100	21.08	-201.48	177.27	3736.83	70.47	1485.44
300	17.35	-203.17	145.90	2531.40	58.00	1006.27
500	17.11	-203.29	143.88	2461.86	57.20	978.62
800	17.63	-203.03	148.26	2613.77	58.93	1039.01
1000	22.45	-200.93	188.79	4238.33	75.05	1684.79

Flexane #30 + 40% P.M.M. Matrix and #30 Jacket.
16, 3-1 Machined Safari PZT elements.
Center hole filled with Tra-bond 2113 epoxy.
Electrode Eccocoat VE silver loaded.

FLEX 38



75
50
25
0
* cycle #1
X cycle #4
g_h $(\times 10^{-3} Vm/N)$
-100
200
500
800
1100
PRESSURE (PSI)

Cycle 01

C= 536.7pf KE= 947.14 KC= 376.5 d33= 313pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	43.70	-195.15	366.47	16014.62	145.68	6366.01
100	37.07	-196.58	310.87	11523.38	123.57	4580.89
300	26.09	-199.63	218.79	5708.24	86.97	2269.09
500	21.86	-201.17	183.32	4007.32	72.87	1592.96
800	21.08	-201.48	176.78	3726.45	70.27	1481.31
1000	17.76	-202.97	148.93	2645.08	59.20	1051.45

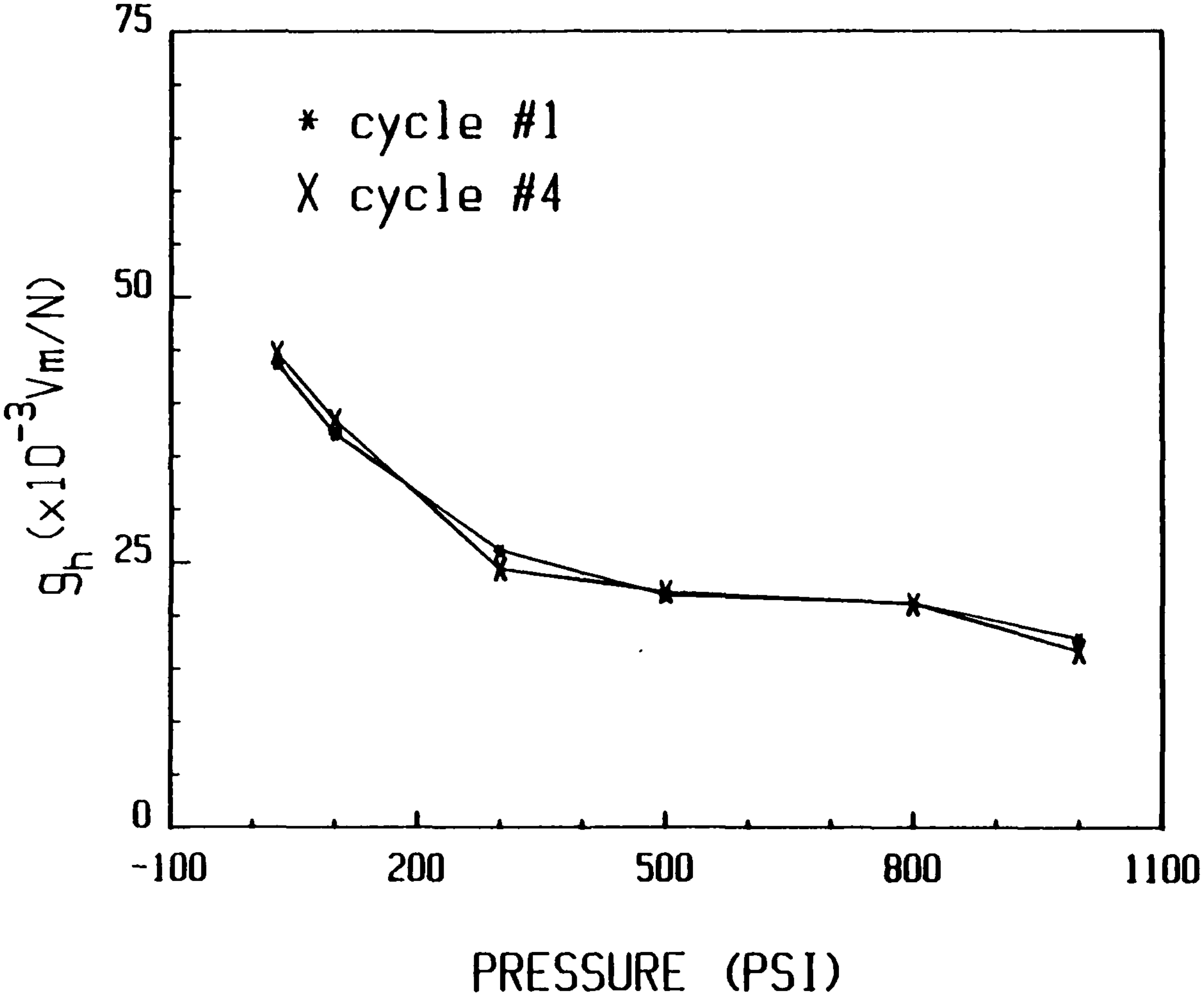
Cycle 04

C= 536.7pf KE= 947.14 KC= 376.5 d33= 313pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	44.69	-194.95	374.77	16748.44	148.98	6657.72
100	38.39	-196.27	321.94	12359.19	127.97	4912.93
300	24.33	-200.24	204.03	4964.07	81.10	1973.28
500	22.15	-201.05	185.75	4114.35	73.84	1635.51
800	21.01	-201.51	176.19	3701.74	70.04	1471.49
1000	16.55	-203.58	133.79	2296.74	55.17	913.06

Flexane #30 + 55% M.B. Matrix and #30 Jacket.
16, 3-1 Machined Safari PZT elements.
Center hole filled with Tra-bond 2113 epoxy.
Electrode Flexane #30 + 45% VME carbon fiber.

FLEX 39



* cycle #1
X cycle #4
75
50
25
0
g_h ($\times 10^{-3}$ Vm/N)
-100
200
500
800
1100
PRESSURE (PSI)

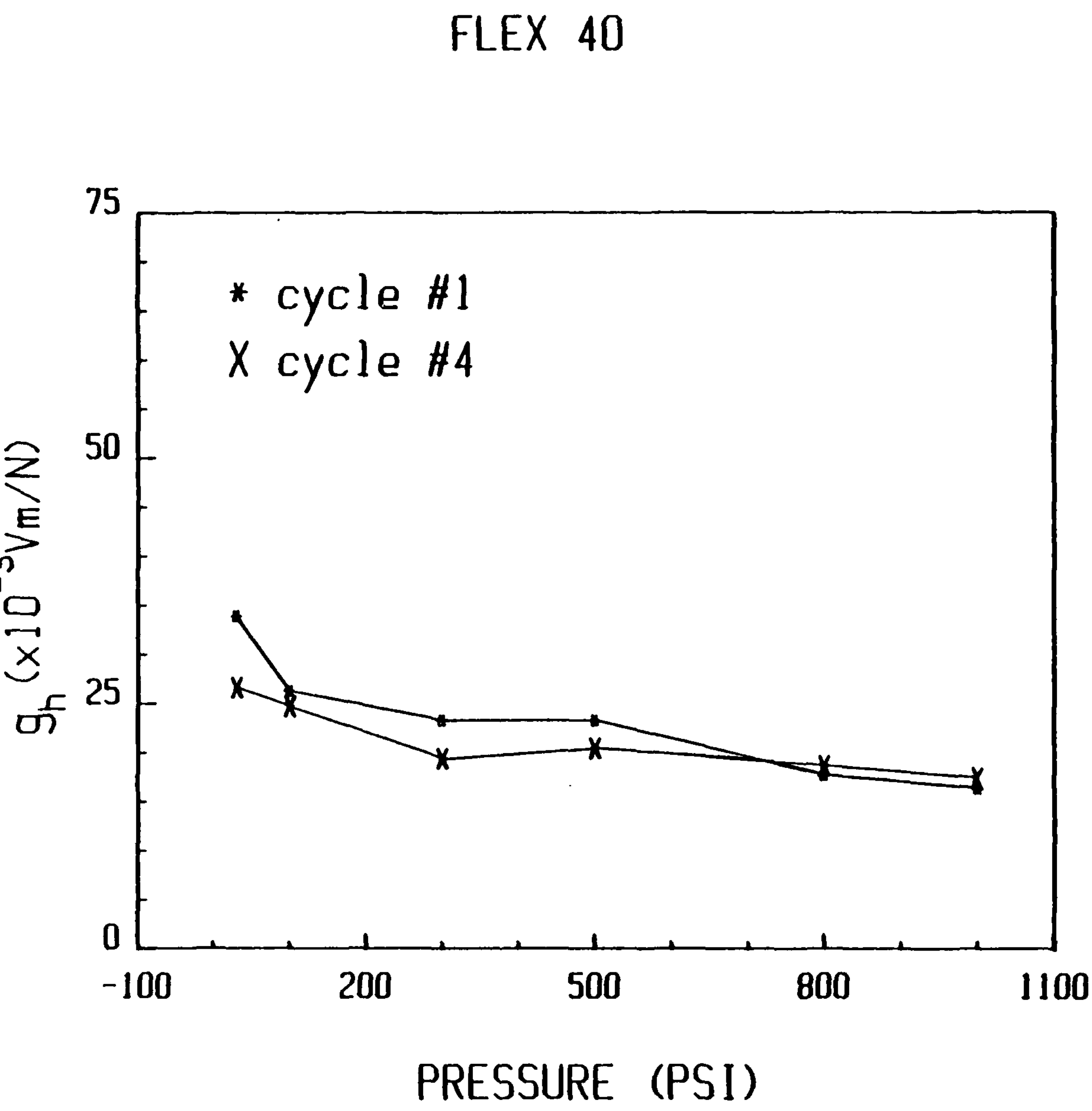
FLEX 40

Cycle 01

C= 541.4pf KE= 955.43 KC= 379.8 d33= 265pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
30	33.90	-197.35	286.77	9721.60	114.00	3864.51
100	26.28	-199.57	222.31	5842.37	88.37	2322.44
300	23.29	-200.62	197.02	4588.57	78.32	1824.04
500	23.29	-200.62	197.02	4588.57	78.32	1824.04
800	17.67	-203.01	149.48	2641.26	59.42	1049.95
1000	16.32	-203.70	138.06	2253.09	54.88	895.64

Flexane #30 foamed Matrix and #30 Jacket.
16, 3-1 Machined Safari PZT elements.
Center hole filled with Tra-bond 2113 epoxy.
Electrode Flexane #30 + 45% VME carbon fiber.


FLEX 40
* cycle #1
X cycle #4
75
50
25
0
-100
200
500
800
1100
g_h ($\times 10^{-3}$Vm/N)
PRESSURE (PSI)

Cycle 01

C= 81.26pf KE= 143.4 KC= 57 d33= 230pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
100	37.32	-196.52	47.38	1768.37	18.83	702.91
300	36.70	-196.67	46.60	1710.10	18.52	679.75
500	36.61	-196.69	46.48	1701.72	18.48	676.42
800	41.25	-195.65	52.37	2160.41	20.82	858.74
1000	39.59	-196.01	50.27	1990.03	19.98	791.02

Cycle 39

C= 80pf KE= 141.18 KC= 56.12 d33= 230pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

			ELEMENT A		COMPOSITE A	
Press PSI	gh Vm/N	Sens db re 1V/uPa	dh C/N	dhgh m2/N	dh C/N	dhgh m2/N
100	36.07	-196.82	45.09	1626.32	17.92	646.47
300	38.39	-196.27	47.99	1842.25	19.08	732.31
600	33.16	-197.55	41.45	1374.49	16.48	546.37
1000	40.71	-195.76	50.89	2071.64	20.23	823.49

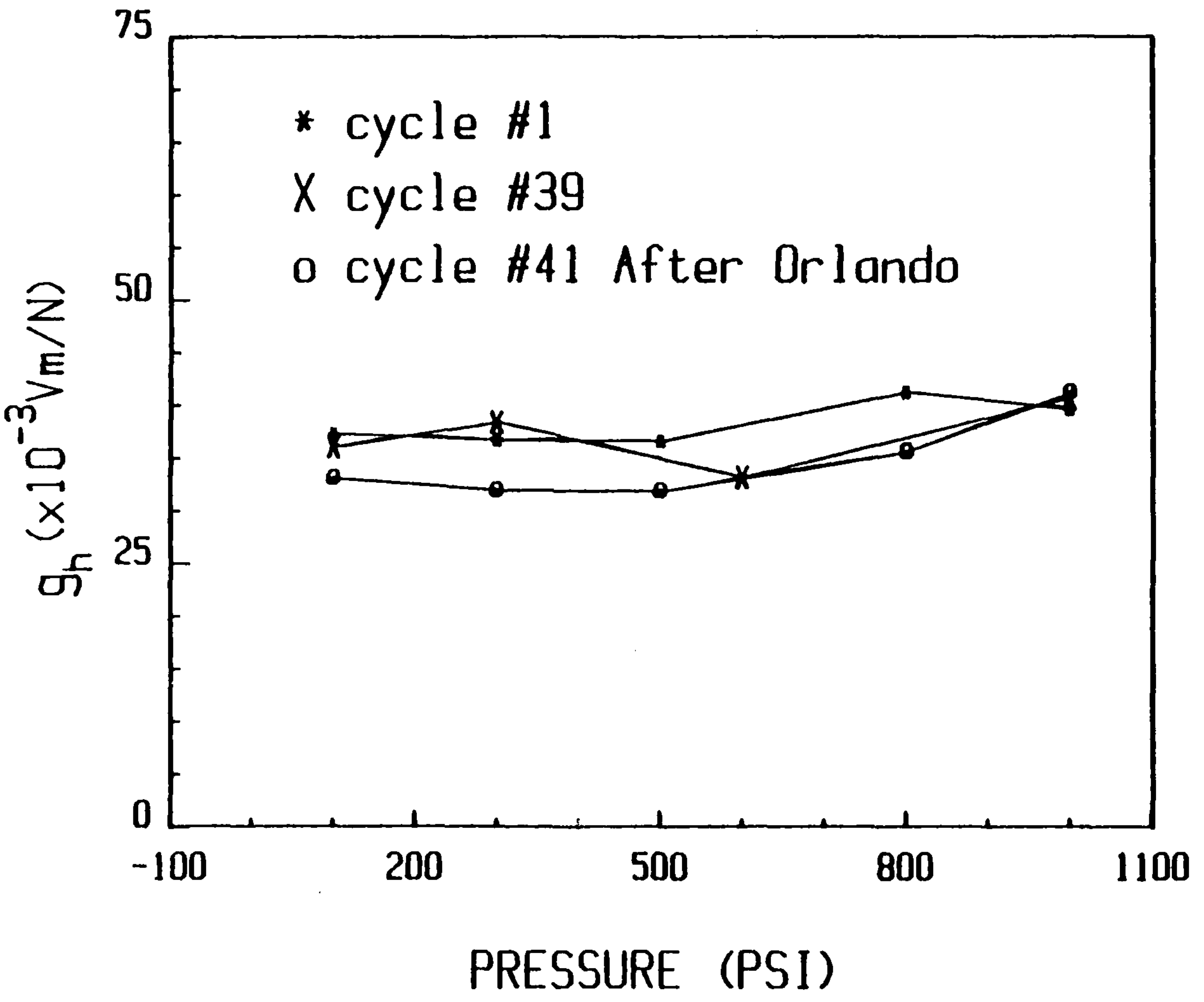
Cycle 41

C= 63.1pf KE= 111.36 KC= 44.27 d33= 230pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	32.12	-197.82	31.67	1017.23	12.59	404.39
100	31.87	-197.89	31.42	1001.46	12.49	398.12
300	33.61	-197.43	33.14	1113.80	13.17	442.78
500	30.53	-198.26	30.10	919.01	11.97	365.34
800	31.36	-198.03	30.92	969.66	12.29	385.48
1000	31.95	-197.87	31.50	1006.49	12.52	400.12

Flexane #60 Matrix and #30 Jacket.
16, 1-3 REN 12mil PZT rod elements.
Electrode Flexane #30 + 45% VME carbon fiber.

FLEX 41



* cycle #1
X cycle #39
o cycle #41 After Orlando
75
50
25
0
g_h $(\times 10^{-3} Vm/N)$
-100
200
500
800
1100
PRESSURE (PSI)

Cycle 01

C= 36.02pf KE= 151.8 KC= 60.34 d33= 200pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
100	32.83	-197.63	44.12	1448.62	17.54	575.82
300	29.27	-198.63	37.34	1131.48	15.64	457.71
500	32.49	-197.72	43.67	1418.77	17.36	563.95
800	26.43	-199.52	35.52	938.87	14.12	373.20
1000	26.37	-199.54	35.44	934.61	14.09	371.51

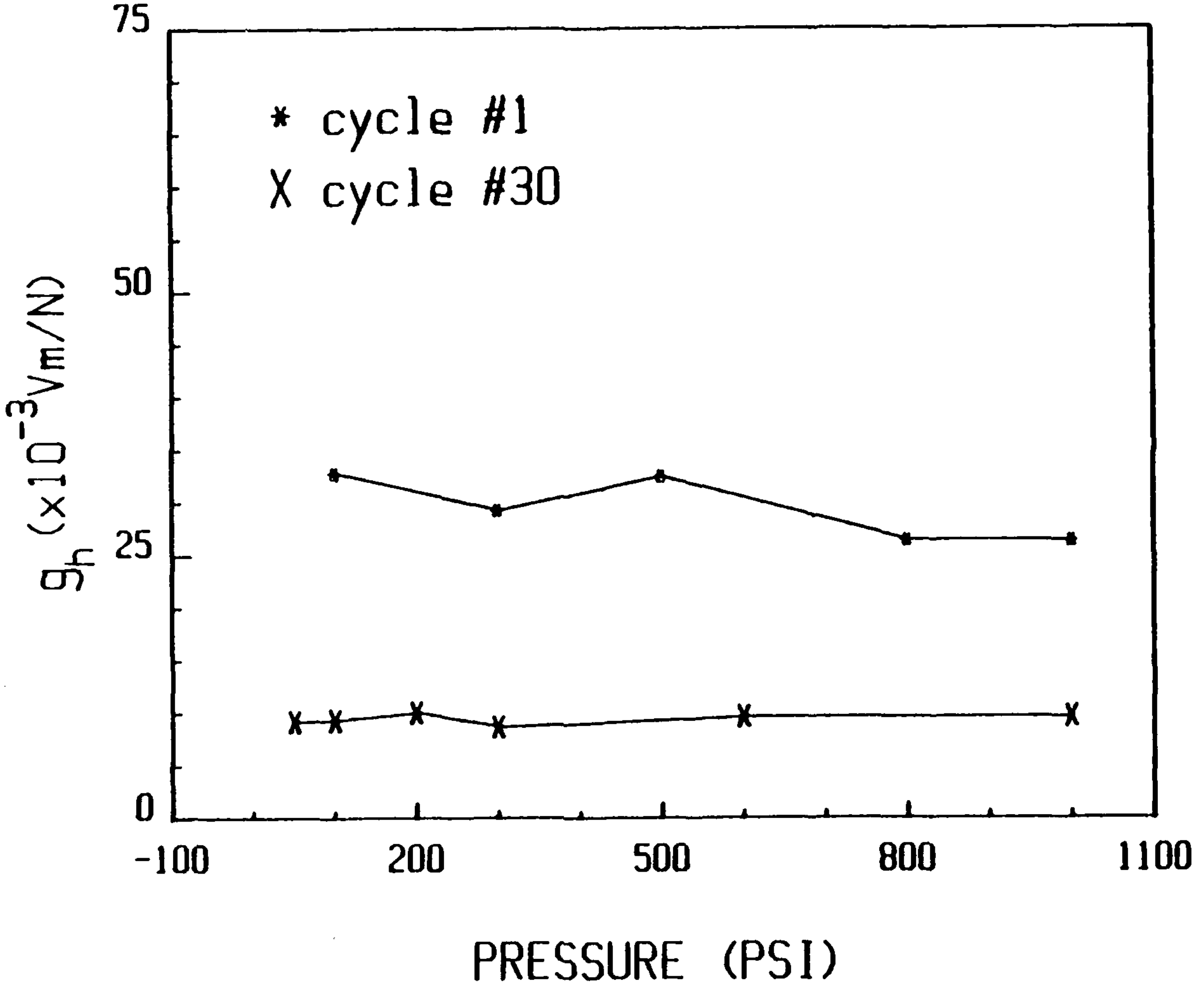
Cycle 30

C= 83.3pf KE= 147 KC= 58.44 d33= 200pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
50	9.20	-208.68	11.97	110.16	4.76	43.80
100	9.36	-208.53	12.18	114.03	4.34	45.00
200	10.04	-207.92	13.07	131.20	5.19	52.16
300	8.70	-209.17	11.32	98.51	4.50	39.16
600	9.68	-208.24	12.60	121.96	5.01	48.48
1000	9.68	-208.24	12.60	121.96	5.01	48.48

Flexane #60 Matrix and #30 Jacket.
16, 1-3 REN 18mil PZT rod elements.
Electrode Flexane #30 - 45% VME carbon fiber.

FLEX 42



* cycle #1
X cycle #30
75
50
25
0
-100
200
500
800
1100
g_h ($\times 10^{-3}$Vm/N)
PRESSURE (PSI)

Cycle 01

C= 88.3pf KE= 155.83 KC= 61.94 d33= 225pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
0	96.90	-188.23	133.69	12955.02	53.14	5149.42
100	63.20	-191.94	87.20	5510.93	34.66	2190.51
300	37.00	-196.59	51.05	1888.84	20.29	750.78
600	38.50	-196.25	53.12	2045.09	21.11	812.89
1000	37.20	-196.55	51.33	1909.31	20.40	758.92

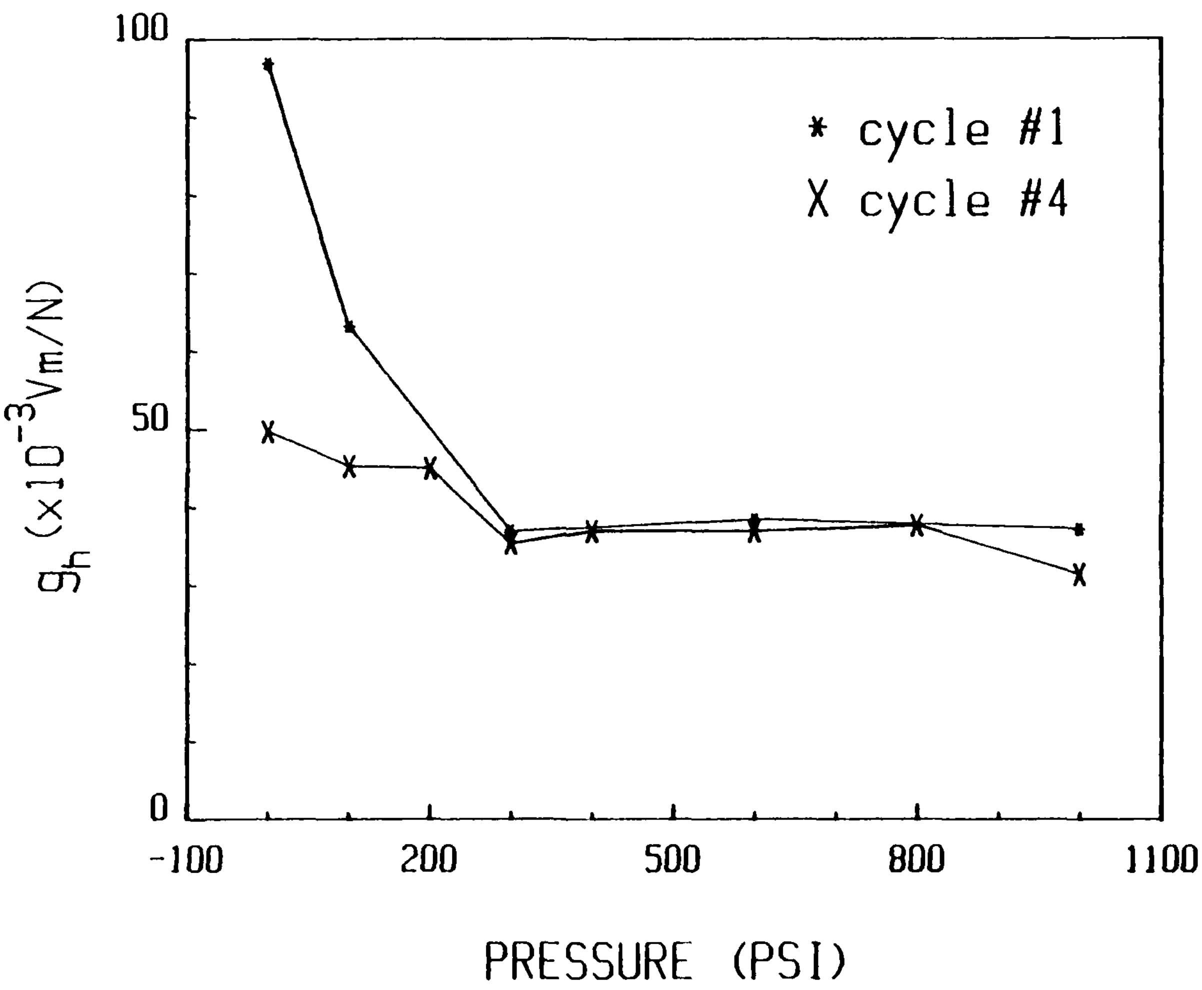
Cycle 04

C= 88.3pf KE= 155.83 KC= 61.94 d33= 225pC/N ELMA= 2.56cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
0	49.70	-194.03	68.57	3408.03	27.26	1354.64
100	45.30	-194.84	62.50	2831.31	24.84	1125.40
200	45.00	-194.89	62.09	2793.93	24.68	1110.54
300	35.40	-196.98	48.84	1729.01	19.41	687.35
400	37.00	-196.59	51.05	1888.84	20.29	750.78
600	37.00	-196.59	51.05	1888.84	20.29	750.78
800	37.70	-196.43	52.02	1960.98	20.68	779.46
1000	31.40	-198.02	43.32	1360.35	17.22	540.72

Flexane #30 + 40% P.M.M. Matrix and #30 Jacket.
16, 1-3 REN 18nil PZT rod elements.
Electrode Flexane #30 + 45% VME carbon fiber.

FLEX 43


100
50
0
g_h (x10^{-3}Vm/N)
* cycle #1
X cycle #4
-100
200
500
800
1100
PRESSURE (PSI)

ECCO 44

Cycle 01

C= 817.62pf KE= 723.45 KC= 573.57 d33= 389pC/N ELMA= 4cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	8.13	-209.76	66.47	540.42	41.29	335.67
100	6.46	-211.75	52.82	341.21	32.81	211.93
300	2.14	-221.35	17.50	37.44	10.87	23.26
500	3.28	-217.64	26.82	87.96	16.66	54.64
700	3.77	-216.43	30.82	116.21	19.15	72.18
1000	4.52	-214.86	36.96	167.04	22.95	103.75

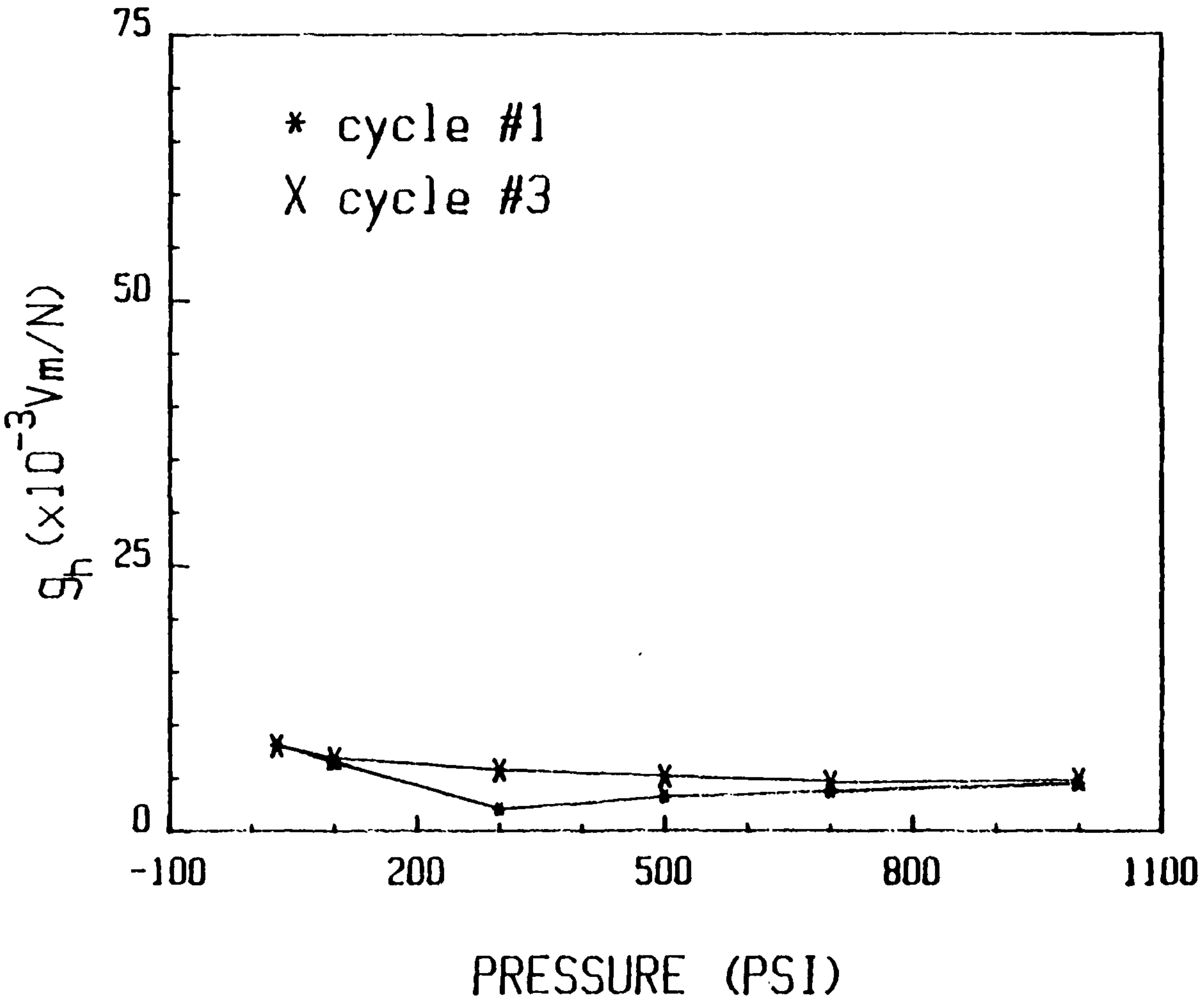
Cycle 03

C= 813.13pf KE= 918.38 KC= 570.42 d33= 389pC/N ELMA= 4cm2
COMPA= 6.44cm2

Press PSI	gh Vm/N	Sens db re 1V/uPa	ELEMENT A dh C/N	ELEMENT A dhgh m2/N	COMPOSITE A dh C/N	COMPOSITE A dhgh m2/N
30	8.05	-209.84	65.46	526.93	40.66	327.23
100	6.89	-211.19	56.02	386.01	34.80	239.76
300	5.77	-212.74	46.92	270.72	29.14	168.13
500	5.16	-213.71	41.96	216.50	26.06	134.47
700	4.60	-214.70	37.40	172.06	23.23	106.87
1000	4.85	-214.24	39.44	191.27	24.49	118.80

Eccogel 1365-45 Matrix and 1365-45 Jacket.
25, 3-1 Machined Safari PZT elements.
Center hole - open.
Electrode Eccogel 1365-0 + Metz fine silver powder and flake.

ECCO 44



* cycle #1
X cycle #3
g_h ($\times 10^{-3}$Vm/N)
75
50
25
0
-100
200
500
800
1100
PRESSURE (PSI)

APPENDIX B

Materials Suppliers

Material	Supplier	Address
PZT 501A	Ultrasonic Powders, Inc.	2383 S. Clinton Ave. South Plainfield, NJ 07080
Gelvatol 20-30 PVA	Monsanto Co.	St. Louis, MO
Litharge (PbO)	Hammond Lead Products	10 S. Grosstown Rod. Pottstown, PA 19464
7095 Silver Frit	DuPont Electrode Matls. Div.	806 Bank of Delaware Wilmington, DE 19898
Zirconia (ZrO_2)	Harshaw Chemical Co.	1945 East 97th St. Cleveland, OH 44106
RP-1774 Epoxy	REN Plastics	5656 S. Cedar St. Lansing, MI 48909
IG-25 Microballoons	Emerson and Cummings, Inc.	Canton, MA 02021
E-Solder #3021	ACME Chem. and Insul. Co. Div. Allied Prod. Corp.	New Haven, CT 06505
Flexane Polyurethanes	Devcon Corp.	Danvers, MA 01923
Eccogel Epoxies	Emerson and Cummings, Inc.	Canton, MA 02021
Metz Ag Powder I-200 Metz #16 AG-Plate	Metz M.M. Corp.	3900 S. Clinton Ave. S. Plainfield, NJ 07080
VME Carbon Fibers	Union Carbide, Inc.	120 S. Riverside Plaza Chicago, IL
Poly Methyl Methacrylate (PMM)	Polysciences, Inc.	Warrington, PA 18976
SPURR (Low Viscosity Epoxy Bedding Kit)	Polysciences, Inc.	Warrington, PA 18976
Trabond 2113 Epoxy	Tra Con	55 North St. Medford, MA 02155

APPENDIX C
Publications

THE INCORPORATION OF RIGID COMPOSITES INTO A CONFORMAL HYDROPHONE

W. SCHULZE, G. DAYTON, D. LAUBSCHER, L. WEBSTER, E. BIBEAU, R. MILLER, B.J. KEARNS, S.R. BRENNEMAN, D. CROSS, H. HAUN, A. NARTHASILPA, B. JONES, A. SAFARI, T. SHROUT, S.-Y. LYNN, R. WILSON AND J. BIGGERS
Materials Research Laboratory, The Pennsylvania State University, University Park, PA 16802

Abstract During the past five years, numerous composite configurations have been analysed for hydrostatic transducer application. Although some of these composite configurations have been flexible, a configuration with good sensitivity and mechanical durability has not bee produced. The need for a sheet or mat, large area transducer that will conform to the hull of a ship has led to the incorporation of small rigid composite elements into a macrocomposite. The goals set for the conformal transducer were sensitivity greater than -200 dB re 1 V/µPa, operation to at least 7 MPa, maximum frequency of 100 Hz, conforming to a 0.10 m radius and a hydrophone section of at least 0.01 m^2.

In the study three types of rigid composites are used to determine the effect of compliant hinge material and flexible electrodes on the hydrostatic sensitivity. Typical response of a 1-3 rod composite in flexible form is a sensitivity of -193 dB re 1 V/µPa, with a capacitance of 14 µf per m^2 and only 2 dB degradation when operating at 7 MPa.

INTRODUCTION

During the past five years the Ferroics Group at the Materials Research Laboratory of The Pennsylvania State University has theoretically and practically explored the use of polymer/ceramic composites as hydrostatic pressure sensors[1]. Advances in the design of these composites have made them interesting candidates to replace traditional tube and sphere based hydrophones for applications that cover large areas and require comformability. A piezoelectric composite approaches the problem of the low hydrostatic sensitivity in PZT (lead zirconate titanate) in a manner similar to that used in existing hydrophones. Both devices increase hydrostatic sensitivity by decoupling the longitudinal and transverse stresses.

Although PZT has large piezoelectric charge coefficient d_{33} and d_{31} (3 is the poling direction), the hydrostatic charge coefficient (d_h), which is the sum of $d_{33}+2d_{31}$ is low. This is because d_{33} is opposite in sign to d_{31} and equal to slightly more than

twice its magnitude. In a properly designed composite, it should be possible to decouple the d_{33} component from d_{31}, enhancing d_h while still maintaining a strong monolithic device. Work with composite hydrophones material has demonstrated the additional advantages of low density, low permittivity, the possibility of increased resistance to mechanical shock and also the possibility of fabrication in flexible form.

DESCRIPTION OF HYDROPHONE

Our goal was to prepare trial hydrophones that were conformable and had a moderate area of 100 cm^2. Evaluation of the various one, two or three dimensionally connected PZT networks has indicated that most truly flexible materials are not physically stable with pressure cycling and have properties that continually change with flexural cycling. For this reason the flexible composite transducers were limited to solid materials that are hinged to make a flexible sheet or a composite-composite. These hydrophones were prepared from three of the most promising composite techniques: (a) a three dimensionally connected PZT-epoxy composite known as BURPS[2]; (b) a one dimensionally connected PZT rod assembly (1-3-0) held together by epoxy loaded with glass spheres[3]; (c) a shape (3-1) that is basically a PZT cube with a cylindrical hole perpendicular to the poling direction[4].

Each test hydrophone was 1/16 the normal active area or 2.5x 2.5 cm and has a thickness of about 0.8 cm. The device is flexible enough to bend around a 4 cm radius. Figure 1 shows a cross-section of this design. The active elements comprise approximately 40% of the hydrophones total area and are held together by insulating polyurethane which gives the device its flexibility. Polyurethane and other viscoelastic polymers have a poisson's ratio of 0.5 and therefore are hydrostatically stiff. This was shown to be a problem when using polyurethane as the matrix in 1-3 composites, and was also found to be a problem when used with these very large cross-section blocks. To alter the poisson's ratio, the polyurethane was filled with glass balloons, polymethyl methacrylate spheres or gas bubbles.

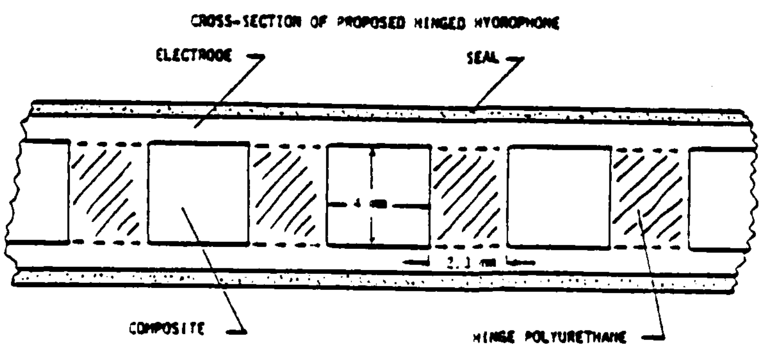


Figure 1. Cross-section of flexible transducer.

The electrode of a flexible composite must endure numerous bends and still maintain a low resistance. In-house experiments with various conductor loaded organics have led to the selection of a dual electrode system. First each rigid element (4x4 mm) of the hydrophone is electroded with highly conducting silver frit or silver epoxy to give a very low resistance across the surface. These electrodes are then tied together by a layer of carbon loaded polyurethane. The carbon loaded polyurethane bonds very well to the polyurethane connecting material and has sufficient conductivity ($5x10^{-2}\ \Omega^{-1}cm^{-1}$) to allow a frequency response to about 100 KHz depending on the capacitance of the elements involved.

The outermost layer is for the purpose of electrical insulation and chemical protection from the environment. This layer has remained the same in all the designs and is the most flexible of the polyurethane series used.

The merits of the three sensing materials were judged to be a combination of sensitivity, durability, and ease of fabrication. A fourth criterion, flexibility, is held constant in this study. The levels of the device response as given in Table 1 depends on the connectivity of the composite and on the properties of the components. The materials used in the following composites are not proposed as a maximized combination but only as the best components selected from a relatively limited number available at our facilities.

The PZT used in all composites will be type 501A produced by Ultrasonic Powders, Inc. Depending on the internal pressures generated, a different type of material may increase sensitivity or stability but this PZT should be a good compromise for the initial samples produced in this study. Even though the green processing and fired shapes are markedly different, experience has shown the properties of the PZT to remain relatively constant.

Table 1. Properties of composite materials.

COMPOSITES

Composite type	Materials Properties					
	K	ρ gr/cm^3	d_h (80 Hz) C/Nx10^{-12}	g_h V·m/Nx10^{-3}	$g_h d_h$ m^2/Nx10^{-15}	d_{33} pC/N
BURPS	400	4.3	45	13	3400	150
1-3-0	100	1.3	55	62	3400	220
3-1 macro-composite	350	5.0	190	23	4400	290

DISCUSSION OF SPECIFIC COMPOSITES

3-1 Macrocomposite

This composite is one of the more recent designs arising from the consideration for mass production (extrusion) and the realization that a totally rigid electrode area transfers the maximum force to the active element while providing a stiffening against the transverse (d_{31}) stresses. The original paper and this study utilize parts produced by ultrasonic drilling, but this should be replaced by extruding a slug of PZT with a cylindrical hole. The tube may then be cut to desired length. A permittivity of 950 and a density of 5 make devices using this material the heaviest and the lowest in electrical impedance of the three composites proposed.

1-3-0

This design is the most difficult to fabricate but also is the system with the most versatility. It is this system that has been constructed as a naturally flexible material although more study is needed to develop a non-dispersive flexible polymer that is not hydrostatically incompressible. The 1-3 composite in this study is a compromise between a high g_h for maximum sensitivity (-193 dB re 1 V/uPa) and an arbitrary minimum capacitance (K-100) of ~1000 pf. There is also a slight frequency and pressure dependency of about 1 dB for 0 to 1000 psi and 20 to 200 Hz.

BURPS

The BURPS technology is perhaps the simplest to fabricate. The solid material is produced by conventional powder/slug fabrication. Once the pores of the three dimensional PZT network are filled with a polymer, the material probably also becomes the most rugged of the candidates. It can then be cut and shaped with normal machining techniques. Electroding is done with conducting epoxy and the material is poled to saturation at 120°C.

The sensitivity of the BURPS composite is the lowest (-203 dB re 1 V/uPa) of the three but has little pressure sensitivity even to 1000 psi. The permittivity of 400 is sufficient to give 3.5 nf capacitance per 10x10 tile.

RESULTS AND DISCUSSION

As was found when exploring the response of 1-3 composites, the matrix (hinge) can strongly influence the response of the PZT (in this case the composite). The #30 flexane is more compliant than the #60 flexane and is believed to be hydrostatically stiffer (poisson's ratio near 0.5). As can be seen in Table 2, the #30 flexane always reduced the response of the composites and in the case where the polyurethane (PU) filled the center of the 1-3, the g_h was reduced to almost that of solid PZT. It appears that the hydrostatically stiff hinge material stiffens the device and removes stress from the composite.

Table 2. Properties of trial sheet hydrophones.

HINGE MATERIAL	Cap./m²	SENSITIVITY	dB CHANGE	g_h	d_h	$g_h d_h$	EXPECTED g_h
	nF/m²	dB re 1V/µPa	at 1000 psi	mV/N	C/N	m²/N	mV/N
3-1							
#30 (PU IN CENTRE)	830	-212	-	6	19	110	-
#30		-206	-1	13	43	560	25
#60		-201	-2	22	75	1650	
#30 FOAMED		-200	-3	25	85	2120	
#30 + 40 v/o MB		-201	-3	23	67	1540	
#30 + 55 v/o MB		-195	-8	45	140	6200	
#30 + 35 v/o PMM		-201	-2	22	75	1650	
#30 + 40 v/o PMM		-202	-1	21	71	1490	
1-3-0							
#60 (6 mil) RODS	320	-198	-1	30	16	480	62
#60 12 mil RODS		-197	0	37	19	700	
#30 + 40 v/o PMM		-192	-3	60	35	2100	

Hydrostatically soft fillers were utilized to reduce the bulk modulous of the #30 flexane to produce a flexible hinge that would not limit the hydrostatic response of the composite elements. The three types of fillers were a) gas bubbles; b) polymethyl methacrylate (PMM) spheres and glass balloons (MB). A second difficulty became evident when using the bubbles. If the hinge is very soft, the stiff carbon fiber electrode acts as a force gathering element and the composite appears to have a response larger than normal at low pressure. This effect drops out at high hydrostatic pressure and the device has the response of a solid hinge configuration. At 1000 psi most devices have the same response at about -203 dB.

The two solid fillers were spherical particles in the order of 100 µm diameter and gave similar sensitivity levels. The PMM spheres were easier to mix with the PU than the microballoon (MB) and gave more pressure stable results. Some of the high values recorded on MB filled PU is attributed to the incorporation of small air bubbles during mixing.

The 1-3-0 elements suffer from the same clamping effect as the 3-1 composite. As expected, the 1-3-0 give a higher g_h sensitivity than the 3-1 but lower d_h because of the reduced permittivity.

The d_h and $g_h d_h$ product of all the devices is lowered considerably from the actual value of the composite because of the increased device area needed for the hinging material. The current design uses a 2.3 mm wide hinge and has more than adequate flexibility. A reduction of the hinge width to 1 mm would increase d_h and $g_h d_h$ by 58%.

Although it was not possible to make sensitivity measurements to 100 kHz, resonance measurements were made on the individual elements and the devices. The 1-3-0 material had a thickness resonance at 200 kHz which was almost totally damped out in device form. The 3-1 material had an unidentified resonance at 140 kHz, but did not exhibit significant noncapacitance impedance until about 250 kHz.

SUMMARY

1) Rigid composite hydrophone material can be incorporated into a conformal sheet hydrophone with sensitivity greater than -200 dB and capacitance greater than 300 nf/m^2.

2) Reduction in flexibility by decreased hinge thickness can signficantly increase sheet capacitance or $g_h d_h$ product.

3) Care must be given to the hinge material to achieve a flexible but still hydrostatically compressible material.

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REFERENCES

1. R.E. Newnham, L.J. Bowen, K.A. Klicker and L.E. Cross, Materials in Engineering 2, 93-106 (1980).

2. K. Rittenmyer, T. Shrout, W.A. Schulze and R.E. Newnham, Ferroelectrics 41, 189-195 (1982).

3. K.A. Klicker, J.V. Biggers and R.E. Newnham, J. Amer. Ceram. Soc. 64(1), 5-9 (1981).

4. A. Safari, R.E. Newnham, L.E. Cross and W.A. Schulze, Ferroelectrics 41, 197-205 (1982).

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